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Field Study of Nutrient Control in a Multicell Lagoon

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La Plata, MD

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16. ABSTRACT This report covers nutrient control in a serially arranged, multicell aerated lagoon system over a three year period. The objective was to develop reliable technology for reducing phosphorus and for converting ammonia-nitrogen to nitrate-nitrogen.

A six-cell lagoon was modified into two independent three-cell systems. One system was maintained as a control and the other was the test system used for nutrient control. Alum was added to the third cell of the test system. Another test was conducted with alum being fed to the first cell. The alum addition in the third cell was more effective in reducing phosphorus.

A plastic media tower was added after the third cell in the test system for nitrification of ammonia-nitrogen. Consistent nitrification was achieved during the warmer months and reduced efficiencies were obtained during the cold weather months.

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FIELD STUDY OF NUTRIENT CONTROL IN A MULTICELL LAGOON

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; for the preservation and treatment of public drinking water supplies, and for the minimization of adverse economic, social, hygienic, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the research and the user community.

This study was conducted in order to develop reliable techniques for removing phosphorus from lagoon effluents. The potential for achieving consistent nitrification using a plastic-media, trickling filter tower was also evaluated.

Francis T. Mayo
Director
Municipal Environmental Research Laboratory

ABSTRACT

Lagoons are well known as acceptable methods of treating both municipal and industrial wastes. The more stringent Federal Discharge Standards have caused the systems to be re-evaluated in terms of efficiency. Modifications to existing facilities appear feasible. This report studied nutrient removal in a serially arranged, multicell, aerated, facultative lagoon system over a 3-year period.

The general objective of this study was to develop reliable techniques for removing phosphorus from lagoon effluents. The potential for achieving consistent nitrification using a plastic-media, trickling filter tower was also evaluated.

A six-cell lagoon system was modified in order to have two independent three-cell systems, one of which was to be the control and the other the test. Each system contained an aerated first cell. Alum addition to the third cell of the test system proved to be more efficient in removing total phosphorus as well as BOD and suspended solids, than alum addition to the first cell.

A plastic-media, trickling filter tower was installed at the effluent station of the third cell of the test system. Consistent nitrification was established; however, seasonal effects caused the system to be less efficient during the winter months.

Lagoons that have been modified to implement these forms of nutrient control should be considered as viable, economic means of meeting current secondary standards.

This report was submitted by the Charles County Community College in fulfillment of Grant No. R803637, sponsored by the U.S. Environmental Protection Agency. It covers the period July 1, 1975, to September 30, 1978, with all work completed by June 30, 1979.

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LIST OF ABBREVIATIONS

a	--	acre
Alk	--	alkalinity - the sum of the bicarbonate, carbonate, and hydroxide ions expressed as $CaCo_3$ mg/ℓ
Alum	--	filter alum - $A1_2(SO_4)_3 \cdot 14H_20(aq)$
Avg	--	average
BOD	--	5-day, 20°C, biochemical oxygen demand, mg/ℓ
COD	--	chemical oxygen demand, mg/ℓ
cm	--	centimeter
DO	--	dissolved oxygen, mg/ℓ
ft	--	feet
g	--	gram
gal	--	gallon
gpm	--	gallon per minute
GM	--	geometric mean
ha	--	hectare
in.	--	inch
kcal	--	kilocalorie
kg	--	kilogram
km	--	kilometer
lb	--	pound
m	--	meter
mg	--	milligram

mi	—	mile
mg/ℓ	—	milligram/liter
MGD	—	million gallons per day
MPN	—	most probable number
NH_3N	—	ammonia nitrogen (mg/ℓ)
NOAA	—	National Oceanographic and Atmospheric Administration
NO_2^-/NO_3^-	—	nitrite-nitrate (mg/ℓ)
O.A.H.	—	outside average height
Phos	—	phosphorus
qt	—	quart
rpm	—	revolutions per minute
sec	—	second
SS	—	suspended solids
$SO_4^=$	—	sulfate
Sol	—	soluble
Std Dev	—	standard deviation
Temp	—	temperature
TKN	—	total Kjeldahl nitrogen
Tot	—	total
Vol	—	volatile
Yr	—	year

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This research project was initiated in 1975 under the direction of Mr. Carl M. Schwing, who is currently Director of Municipal Utilities in Galveston, Texas. His advice and expertise have been extremely helpful, not only during the field work but also throughout the formulation of this report.

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SECTION 1

INTRODUCTION

During the last 25 years, lagoons (wastewater stabilization ponds) have gained increasing popularity as an economically attractive method of wastewater treatment for small and emerging population centers. However, their ability to consistently meet the secondary treatment standards promulgated by the Federal Water Pollution Control Act Amendments (P. L. 92-500) is in question. The Clean Water Bill of 1977 (1), raised certain limits of lagoon standards. For example, the effluent limits for suspended solids in lagoons for the State of Maryland have been changed from 30 mg/ℓ to 90 mg/ℓ (2).

In contrast to their increased usage since 1960, lagoons have received relatively little attention from the engineering community. The complex and uncontrolled character of the lagoon treatment process presents an inherently difficult problem to study. Thus, useful data are not easily generated. Since lagoons are simple to operate, they do not require the attention of an operator on a regular basis. As a result, operational data collected prior to 1972 was amassed slowly and without the benefit of an overall plan with specific objectives.

In 1973, the U.S. Environmental Protection Agency (EPA) began a program to formalize and upgrade lagoon technology. Its objective was to determine the viability of the lagoon as a secondary treatment process, capable of meeting Federal and State effluent quality standards. This program incorporated studies of several lagoon systems throughout the United States. Each study was directed to assess a specific problem or set of problems. The St. Charles Communities lagoon system located in Waldorf, Maryland, was selected as one of the research sites. Using this system, the Charles County Community College, La Plata, Maryland, conducted a 3-year study, whose clearly defined objectives are outlined as follows:

1. To develop reliable techniques consistent with the basic simplicity of lagoon operation for removing phosphorus and unoxidized nitrogen from lagoon effluents.

2. To evaluate the potential for achieving consistent nitrification by using a plastic media, trickling filter tower that will treat a sidestream of effluent from the last cell of the test series.

SECONDARY OBJECTIVES

1. To generate reliable, long-term performance data on a three-cell combined, aerated-facultative lagoon which does not have alum added, which is operated in parallel with the test system, and which serves as a control.

2. To assess the effect of alum addition, not only on phosphorus removal but also on suspended solids and organic removals.

3. To determine the additional costs and operating requirements necessitated by the nutrient control procedures.

The results presented in this report were obtained from data collected over a period of 36 months. Fifteen parameters were studied at nine key sample locations.

SECTION 2

CONCLUSIONS

1. Statistical analysis indicated that the first two cells of the test and control systems performed comparably.

2. Statistical analysis indicated that the first two cells of the system produced an effluent similar in water quality to the three-cell system.

3. The effluent from the first two cells of the three-cell system whose first cell is aerated met the existing secondary standard of 30 mg/ℓ for BOD.

4. The majority of soluble BOD was converted to insoluble BOD in the aerated first cell.

5. Very little conversion of soluble BOD to insoluble BOD occurred in the second and third cells.

6. The secondary BOD standard of 30 mg/ℓ could be met when alum was added to the third cell of the three-cell test lagoon system.

7. Alum addition to the third cell of a three-cell system is more efficient in removing BOD and suspended solids than alum addition to the first cell of the system.

8. A two- or three-cell system whose first cell is aerated did not meet the existing secondary standard of 30 mg/ℓ for suspended solids.

9. A two- or three-cell system whose first cell is aerated will meet the existing State of Maryland effluent lagoon standard of 90 mg/ℓ for suspended solids.

10. The suspended solids standard of 30 mg/ℓ could not be met consistently when alum was added to the third cell of the test system; however, the state of Maryland standard of 90 mg/ℓ was met consistently.

11. The secondary standard of 200 MPN/100 mℓ for fecal coliform could not be achieved without chlorination of the three-cell lagoon effluent.

12. The three-cell lagoon system produced an average total phosphorus concentration of 6.6 mg/ℓ and an average soluble phosphorus concentration of 5.8 mg/ℓ in the final effluent.

13. The addition of alum to the final cell of the three-cell test lagoon system produced an annual total phosphorus concentration of 2.5 mg/ℓ and a soluble phosphorus concentration of 1.6 mg/ℓ in the final effluent. This represents an 81% reduction in total and an 85% reduction in soluble phosphorus.

14. The addition of alum to the first cell of a three-cell system produced an annual total phosphorus concentration of 4.1 mg/ℓ and a soluble phosphorus concentration of 3.2 mg/ℓ. This represents a 60% reduction in total and a 75% reduction in soluble phosphorus concentrations.

15. Alum addition to the third cell of a three-cell system produced lower total and soluble phosphorus concentrations in the final effluent than alum addition to the first cell of a system.

16. The highest ammonia reduction occurred in the aerated first cell.

17. The nitrite/nitrate concentration did not increase significantly after the first aerated cell.

18. A nitrification tower performed at an efficiency of 83% $\pm$ 2% on the effluent of a three-cell lagoon system.

19. Increases in pH, temperature, and DO led to increased nitrification.

20. The acid content destroys alkalinity at a ratio of 6.9 mg $CaCO_3$/1.0 mg NH_3.

SECTION 3

RECOMMENDATIONS

1. A three-cell lagoon system should be studied to determine the efficiency of batch- versus continuous-chemical addition for phosphorus removal.

2. The feasibility of using slow- and high-rate sand filters for upgrading three-cell lagoon effluents to meet the secondary standard of 30 mg/ℓ suspended solids should be evaluated.

3. In lagoons with seasonal- or batch-discharge, flow meters should be installed on the influent and effluent lines to improve monitoring of the true loadings into the system.

4. The use of a mechanical clarifier to settle the chemical floc should be evaluated on the alum-treated effluent in lieu of a third cell.

5. Annual performance evaluations of the overall efficiency of a lagoon system, as well as the individual cell efficiencies, should be conducted to establish a bank of control data and identify problem areas affecting performance.

6. Lagoon designs should provide for representative sampling of influent, intralagoon transfers, and effluent streams.

7. The use of a nitrification tower on the effluent of a three-cell lagoon system to which no alum has been added should be evaluated.

8. The feasibility of a settling mechanism for the removal of solids in the tower effluent should be studied.

9. Since the final effluent of this lagoon system is disposed of by spray irrigation,

   a. the effect of an alum-treated effluent in a land treatment operation should be studied; and

   b. the effect of a nitrified-lagoon effluent in a land treatment operation should be studied.

10. Considering the popularity and economic operating cost of lagoons, the data compiled in this project should be used in setting attainable effluent limitations and adequate design guidelines.

SECTION 4

LITERATURE REVIEW

Wastewater stabilization ponds have been used extensively as a means of treating wastewater. These ponds have been defined as "basins natural or artifical, designed or used to treat organic waste by natural biological, biochemical, and physical processes." (3) The concept appears to have evolved from practices associated with land disposal of sewage effluents in areas with semi-arid and arid climatic conditions. It was not until the 1920's that history first recorded information on ponds being used for wastewater treatment. After World War II, wastewater treatment lagoons were accepted as a dependable engineered system for the treatment of municipal and industrial wastes in the United States.

Prior to the enactment of the 1977 secondary treatment standards, EPA believed that the majority of existing lagoon systems would fail to meet the new requirements. This feeling was based on the paucity of concrete performance data indicating existing lagoons could meet the new standards and on Barsom's comprehensive report on lagoon performance (4). Barsom evaluated data on 3,000 lagoon systems from 50 States and concluded that the suitability of lagoons as secondary treatment systems was highly questionable.

Previous government-funded lagoon studies included those completed by Barsom (4), as cited above, Champlin (5), and Christianson (6). Although these earlier programs provided much needed information on lagoon systems, they failed to deal effectively with the problems of poor lagoon design and inadequate lagoon treatment technology. These problems were addressed at the symposium held at the Utah State University (7) in August 1974, and as a result, EPA launched a program to upgrade existing lagoon systems to meet new discharge standards.

The objectives of the upgrading program were to be accomplished by providing guidelines developed through major research in the following areas: low-cost suspended solids and algae removal, nutrient control, effluent discharge to the land, and disinfection and control of weeds and other undesirable growth.

Lagoon Performance

A major concern in the program was the general lack of long-term performance data on existing lagoon systems. To provide this needed information early in the program, several Environmental Protection Agency-funded studies were initiated during 1974 at different climatic regions in the United States. These studies were designed specifically to generate prospective long-term performance data and to determine whether existing, well-designed, continuous-discharge, multicelled lagoons would be able to meet the 1977 discharge standards.

The results of these studies did not entirely confirm earlier negative feelings regarding the adequacy of lagoons as secondary treatment facilities. Reynolds et al. (8) evaluated a seven-celled lagoon system in Corinne, Utah, and determined that the Federal secondary standard of 30 mg/ℓ BOD_5 and 30 mg/ℓ suspended solids were met 100% and 70% of the time, respectively. Bowen (9), in studying a three-celled lagoon system in Peterborough, New Hampshire, showed that secondary standards for BOD_5 and suspended solids were consistently met except for an 11-week winter period when the BOD_5 averaged 45 mg/ℓ. McKinney (10), in evaluating a three-celled lagoon in Eudora, Kansas, concluded that the system could not meet EPA standards because of excessive suspended solids in the final effluent.

Nutrient Control

In addition to more stringent secondary standards, major efforts are being directed toward nutrient control in wastewater effluents. The eutrophication of receiving water systems is greatly accelerated when compounds of phosphorus and nitrogen are introduced in excessive amounts. Nitrogen in the form of ammonia interferes with chlorination and exerts a considerable oxygen demand on receiving systems. Under ideal conditions, excessive nutrient input may result in massive algal blooms followed by extensive fish kills and the destruction of other aquatic organisms. In an effort to help preclude these adverse effects, major research has recently been initiated to develop nutrient control technology.

Phosphorus Removal

Until recently, technology in phosphorus removal has been developed mainly through research at conventional treatment plants. This has traditionally been conducted by studying the effects of the addition of various coagulants at different points in the treatment system. Technological developments dealing specifically with the removal of phosphorus from lagoon effluents are few. Many reports on phosphorus removal in lagoons are only byproducts of major research on algae removal by addition of coagulants. Shindala and Stewart (11) studied the application of several coagulants on a post treatment process to remove algae and improve the quality of effluents from lagoons. They concluded that the optimum dosage for best removal of the parameters studied was 75 to 100 mg/ℓ of alum. They also presented a model to relate the degree of phosphate removal to coagulant dosage. Discussions at the Sixth Mississippi Water Resources Conference (12) resulted in the opinion that chemical coagulation was effective in removing algae and phosphorus from lagoon effluents. In addition, alum was determined to be the most effective coagulant.

In recent years, the Canadian Ministry of the Environment has demonstrated great concern in nutrient removal from lagoons by initiating extensive research in this field. In an investigation on phosphorus removal from lagoons, Graham and Hunsinger (13) concluded that batch-chemical treatment of seasonal retention lagoons with alum or ferric chloride was an effective means of reducing the total phosphorus in pond effluent to below 1.0 mg/ℓ. Boyko and Pupke (14) have discussed the problems and design considerations derived from full-scale research on phosphorus removal from lagoons and conventional treatment plants. Included in their report are operational results of past studies.

Nitrification

Nitrification of wastewater does not remove nitrogen but converts ammonia to nitrites and nitrates. The primary advantage to this process is an overall reduction in the total oxygen demand exerted on the receiving water system. Numerous studies have been conducted on nitrification and technology has expanded to include the combined carbon-oxidation-nitrification process and the separate-stage nitrification process. Both of these processes may be further categorized as suspended-growth processes or attached-growth processes.

Recent research on the nitrification of lagoon effluents using a plastic-media trickling filter is limited. The most comprehensive report available on nitrification utilizing a plastic-media trickling filter was conducted at a conventional treatment plant by Duddles and Richardson (15). They found that plastic-media trickling filters are capable of achieving consistent, high-level nitrification (>90%) when the tower influent contained 15-30 mg/ℓ BOD_5 and ammonia concentration in the range of 10-20 mg/ℓ. They reported that the system produced consistent and stable performance during both summer and winter climates. Stone et al. (16) studied nitrification using a plastic-media trickling filter at the Sunnyvale, California, oxidation ponds; however, they only reported surface area requirements to achieve a certain ammonia concentration in the effluent.

Borchardt et al. (17) initiated a nitrification study at Genoa, Ohio, utilizing a rotating biological disc in a two-stage, flow-through lagoon. However, this investigation was discontinued because of high algae densities, low NH_3 concentrations, precipitating calcium carbonate, and low environmental temperatures.

SECTION 5

EXPERIMENTAL METHODOLOGY

STUDY LOCATION

The study was conducted at the St. Charles Communities wastewater lagoon system, Waldorf, Maryland. St. Charles Communities is located in Charles County, Maryland, approximately 40 km (25 mi) south of Washington, D.C. The community is a model city, privately developed by Interstate General Corporation and partially funded by a Housing and Urban Development grant.

The community has a population of 8,000 and covers an area of approximately 3,200 ha (8,000 a). There are a variety of housing models including single, duplex and triplex houses as well as townhouses, multiresidential apartments and condominiums. The community is sectioned with neighborhood centers. Nonresidential structures include schools, churches, service stations, food marts, and a library. In addition, there is an industrial park with light manufacturing and service oriented companies.

On September 1, 1978, there were 1,758 connections to the water and sewer system. These consisted of:

1733 Simplex Houses
18 Duplex Houses
5 Nonprofit
2 Industrial

All triplex, townhouses and apartments are connected to the new lagoons (Cells G, H, and I). All simplex and triplex dwellings constructed since 1975 (other than those listed above) were connected to the new lagoons.

The average water consumption was 79.7 m^3 (21,048 gal) per residence per month for the period November 1, 1978, to January 31, 1979.

LAGOON SYSTEM

The St. Charles lagoon system consists of nine cells as depicted in Figure 1. Cells A, B, and C were constructed in 1966 and Cells D, E, and F were constructed in 1969. The cells indicated as G, H, and I were constructed in 1971.

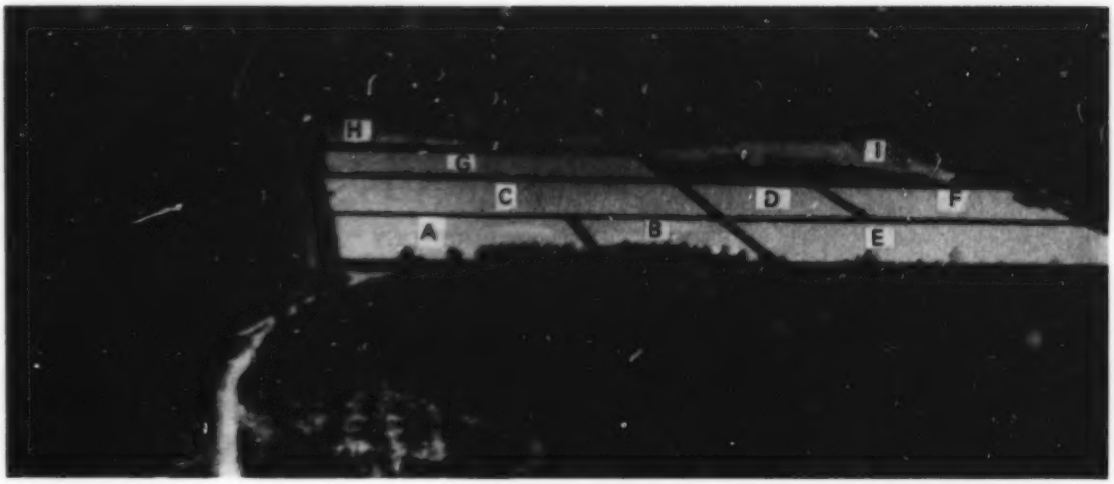

Figure 1. Aerial photograph—St. Charles Lagoon System.

This study utilized Cells A through F. Although all nine cells can be interconnected, Cells A through F and Cells G, H, and I have been historically, and were for the duration of this study, operated as separate systems. Influent to the two lagoon systems originates in different neighborhoods in the St. Charles Communities.

The lagoon system under study was designed for either parallel or series operation between the six cells. Prior to the 1969 lagoon expansion, Cells A, B, and C were operated as depicted in Figure 2.

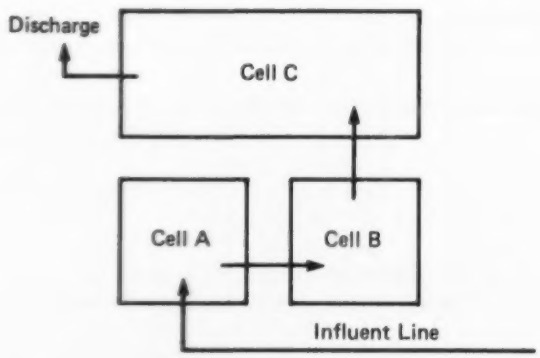

Figure 2. Lagoon Operation prior to 1969.

After the 1969 expansion, Cells A and B were operated in parallel, followed by serial operation of Cells C through F as depicted in Figure 3.

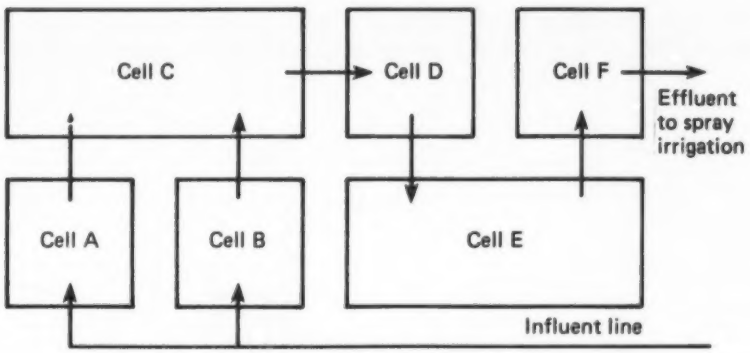

Figure 3. Serial flow pattern prior to study.

During this study, the system was operated so that there were two, three-cell parallel systems. Cells A, C, and D were the test system, and Cells B, E, and F served as the control system. Each system has a total surface area of 4.04 ha (10 a). The average depth of all the ponds is approximately 1.22 m (4 ft). The flow pattern through each system and the size of each are represented in Figure 4.

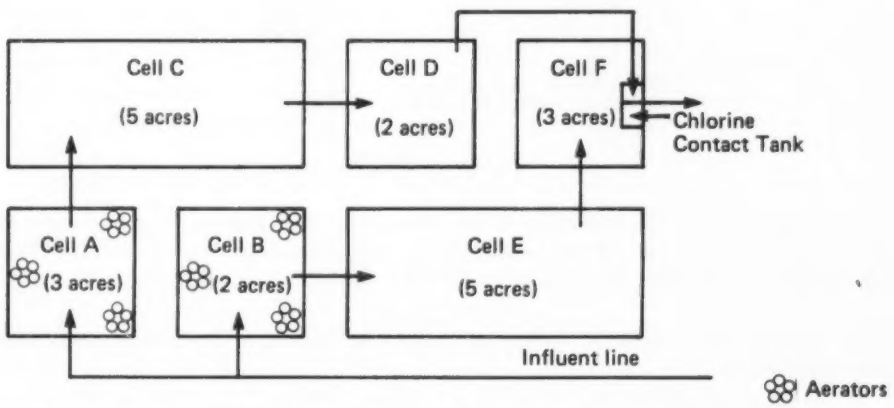

Figure 4. Lagoon study area (A, C, D—Test system; B, E, F—Control system).

The design of Cells A through F was based on a projected population of 6,000 and a flow of 2,300 m^3/day (0.6 MGD). Based on the design flow and assuming equal flow distribution, the average detention time for each system is 54 days.

Both Cells A and B have three, floating 5-horsepower, mechanical aerators which were installed during the 1969 expansion. Each aerator has an oxygen transfer rate of 2.7 kg/hr (6 lb/hr). The aerators operate 24 hours per day annually, except during periods of severe freezing.

The test and control systems are fed from a common influent pump station located approximately 540 m (1,800 ft) from the treatment site. The influent flow into the lagoon system was calculated using elapsed time meters and raw wastewater pump capacities. The influent receives no preliminary treatment before entering Cells A and B.

Effluent disposal is by land application through spray irrigation and is operated for approximately 7 hours per day. During periods of cold weather, spray irrigation is restricted to sunlight hours. The water level is permitted to rise in the cells until seasonal weather conditions permit discharge.

During this study the effluent from the control system flowed into the chlorine contact tank for final disposal. (See Figure 5.) The effluent from the test system passed from Cell D into Cell F for final discharge during

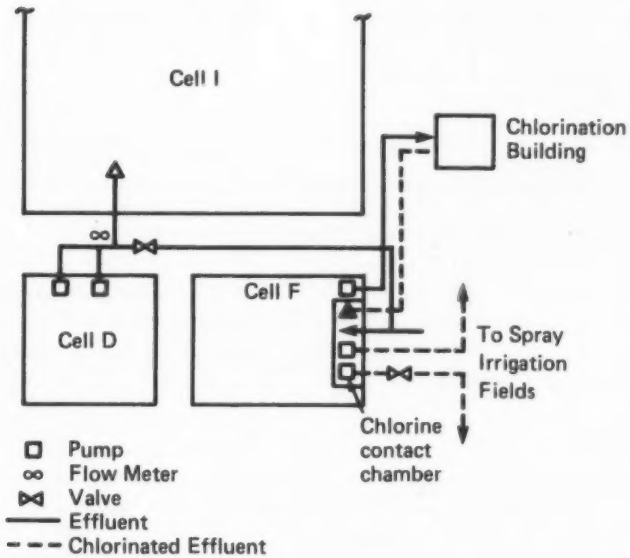

Figure 5. Effluent system.

the first 12 months of the study, September 1975 to September 1976. Subsequent to September 1976, the effluent of the control system was pumped from the southwest corner of Cell D by two, 1.7-m^3/day (460-gpm) Hydromatic submersible pumps, Model 5H200, which were connected in parallel to a common discharge header.

The effluent from Cell D could either be pumped to Cell I or to the chlorine contact tank at the end of Cell F as shown in Figure 5.

Two propeller flow meters were located at the pump station in the chlorine contact chamber and recorded the total discharge from Cell F. One, 20-cm (8-in), Badger propeller flow meter was located in the effluent line from Cell D and recorded the total discharge from the test system. Tables 1 and 2 show all influent and effluent flow values for the project.

TABLE 1. INFLUENT AND EFFLUENT FLOWS (TOTAL)

Year/Month	Influent				Effluent			
	Total MG	(m^3)	Avg. MGD	(m^3/d)	Total MG	(m^3)	Avg. MGD	(m^3/d)
1975/July	17.2	(65,102)	.556	(2104)	20.9	(79,107)	.675	(2555)
Aug	16.1	(60,939)	.519	(1964)	18.9	(71,537)	.609	(2305)
Sep	17.8	(67,373)	.593	(2245)	20.4	(77,214)	.679	(2570)
Oct	20.1	(76,079)	.649	(2457)	24.8	(93,868)	.801	(3032)
Nov	16.4	(62,074)	.548	(2074)	18.3	(69,266)	.609	(2305)
Dec	16.0	(60,560)	.515	(1949)	18.2	(68,887)	.588	(2226)
1975 Average	17.3	(65,355)	.563	(2132)	20.3	(76,647)	.660	(2499)
1976/Jan	19.0	(71,915)	.613	(2320)	12.4	(46,934)	.401	(1518)
Feb	11.3	(42,771)	.391	(1480)	18.8	(71,158)	.673	(2547)
Mar	18.7	(70,780)	.604	(2286)	20.9	(79,107)	.676	(2559)
Apr	18.1	(68,509)	.602	(2278)	23.0	(87,055)	.767	(2903)
May	17.4	(65,859)	.560	(2120)	20.8	(78,728)	.672	(2544)
June	15.5	(58,668)	.518	(1961)	15.8	(59,803)	.528	(1998)
July	15.4	(58,289)	.499	(1889)	16.9	(63,967)	.545	(2062)
Aug	16.5	(62,453)	.532	(2013)	17.8	(67,373)	.575	(2176)
Sep	16.4	(62,074)	.546	(2066)	20.8	(78,728)	.693	(2623)
Oct	19.0	(71,915)	.613	(2320)	18.8	(71,158)	.783	(2963)
Nov	19.2	(72,672)	.641	(2426)	20.9	(79,107)	.698	(2642)
Dec	20.0	(75,700)	.646	(2445)	15.0	(56,775)	.471	(1782)
1976 Average	17.2	(65,134)	.564	(2134)	18.5	(69,991)	.624	(2360)
1977/Jan	20.3	(76,836)	.656	(2483)	16.1	(60,939)	.518	(1960)
Feb	17.4	(65,859)	.622	(2354)	16.8	(63,588)	.601	(2275)
Mar	20.2	(76,457)	.651	(2464)	23.9	(90,462)	.772	(2922)
Apr	20.2	(76,457)	.674	(2551)	17.5	(66,238)	.582	(2203)
May	22.0	(83,270)	.707	(2676)	20.2	(76,457)	.657	(2486)
June	19.3	(73,051)	.642	(2430)	19.1	(72,294)	.637	(2411)
July	19.8	(74,943)	.638	(2415)	NA	NA	NA	NA
Aug	21.9	(82,892)	.705	(2668)	19.8	(74,943)	.710	(2800)
Sep	15.4	(58,289)	.514	(1945)	16.2	(61,317)	.541	(2048)
Oct	16.2	(61,317)	.523	(1980)	14.0	(52,990)	.453	(1715)
Nov	18.9	(71,537)	.631	(2388)	19.0	(71,915)	.635	(2403)
Dec	22.8	(86,298)	.734	(2778)	24.6	(93,111)	.794	(3005)
1977 Average	20.9	(73,934)	.641	(2165)	18.8	(71,296)	.627	(2384)
1978/Jan	30.8	(116,578)	.994	(3766)	25.5	(96,518)	.821	(3107)
Feb	24.1	(91,219)	.861	(3258)	25.5	(96,518)	.910	(3444)
Mar	28.2	(106,737)	.909	(3440)	26.6	(100,681)	.859	(3251)
Apr	23.8	(90,083)	.794	(3005)	18.8	(71,158)	.628	(2377)
May	33.6	(127,176)	1.084	(4103)	25.0	(94,625)	.805	(3047)
June	23.9	(90,462)	.799	(3024)	22.5	(85,163)	.750	(2839)
July	23.7	(89,705)	.763	(2888)	21.6	(81,756)	.696	(2634)
Aug	23.8	(90,083)	.766	(2899)	20.5	(77,971)	.663	(2509)
Sep	20.8	(78,728)	.694	(2627)	19.1	(72,294)	.637	(2411)
1978 Average	25.9	(97,863)	.852	(2683)	22.8	(86,298)	.752	(2847)

TABLE 2. TEST AND CONTROL SYSTEM EFFLUENT FLOWS

	Test System				Control System			
Year/Month	Total MG	(m^3)	Avg. MGD	(m^3/d)	Total MG	(m^3)	Avg. MGD	(m^3/d)
1976/Sep*	8.7	(32,930)	.414	(1567)	8.0	(30,280)	.383	(1450)
Oct.	9.0	(34,065)	.376	(1423)	9.8	(37,093)	.407	(1540)
1976 Average	8.6	(33,496)	.395	(1495)	8.9	(33,686)	.395	(1495)
1977/July**	0.8	(3,028)	.165	(625)	3.0	(11,355)	.609	(2305)
Aug	5.6	(21,196)	.279	(1058)	14.3	(54,126)	.461	(1745)
Sep	5.8	(21,953)	.193	(731)	10.5	(39,743)	.349	(1321)
Oct	2.8	(10,598)	.092	(348)	11.2	(42,392)	.361	(1366)
Nov	6.3	(23,846)	.211	(799)	12.7	(48,070)	.424	(1604)
Dec	7.6	(28,766)	.244	(923)	17.0	(64,345)	.550	(2082)
1977 Average	4.8	(18,231)	.247	(747)	34.4	(43,339)	.459	(1737)
1978/Jan	6.9	(26,117)	.223	(844)	18.6	(70,401)	.599	(2267)
Feb	13.5	(51,098)	.481	(1820)	12.0	(45,420)	.428	(1620)
Mar	16.6	(62,831)	.534	(2021)	10.1	(38,229)	.325	(1230)
Apr	8.2	(31,037)	.273	(1033)	10.6	(40,121)	.355	(1344)
May	13.9	(52,612)	.488	(1696)	11.1	(42,014)	.357	(1351)
June	14.1	(53,369)	.470	(1779)	8.4	(31,794)	.280	(1060)
July	11.5	(43,528)	.371	(1404)	10.1	(38,229)	.325	(1230)
Aug	14.7	(55,640)	.473	(1790)	5.9	(22,332)	.190	(719)
Sep	12.1	(45,799)	.402	(1522)	7.1	(26,874)	.235	(889)
1978 Average	12.4	(46,892)	.413	(1545)	10.4	(39,490)	.344	(1301)

* September 10 - 30
** July 26 - 30

Study Procedures

In order to maintain the highest degree of validity of the results of this study, to ensure the usefulness of the technology developed, and to maintain the integrity of the system, the study did not modify the normal operation and maintenance of the system. These tasks were accomplished by the St. Charles Utilities. All phases of the project were coordinated through the operations group. In addition, approval for the project was obtained from the Maryland State Clearinghouse through the Maryland Water Resources Administration, the Maryland State Department of Health and Mental Hygiene and the Tri-County Council for Southern Maryland.

To achieve the tasks of the project, simultaneous studies were conducted. Figure 6 presents a time graph depicting the sequencing of the tasks.

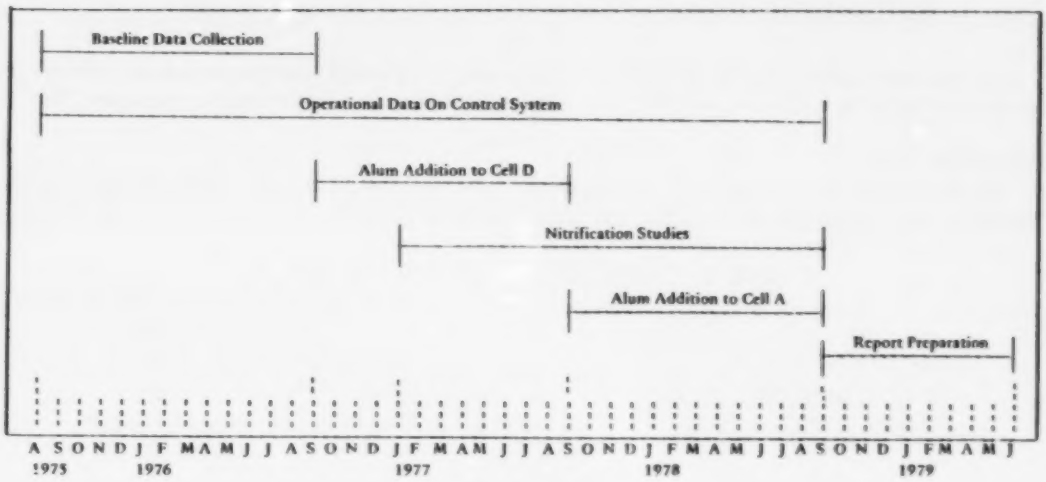
Baseline Data Collection
Operational Data On Control System
Alum Addition to Cell D
Nitrification Studies
Alum Addition to Cell A
Report Preparation
A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
1975
1976
1977
1978
1979

Figure 6. Schedule of project tasks.

Baseline Data

During the period from August 1975 to September 1978, data were collected on control Cells B, E, and F. These data were used to establish long-term background data on a three-cell series lagoon system and to serve as a basis for evaluating data from the test system. Data from the test system were collected from August 1975 to September 1976. These data served to establish baseline concentrations and efficiencies in Cells A, C, and D.

Phosphorus Study

Phosphorus removal studies were conducted from August 1976 to September 1978. The study was designed to investigate phosphorus removal by the addition of alum to the influent of the first cell (an aerated cell in this case) or to the influent of the third cell of the three-cell system. The results were evaluated on the basis of removal efficiency, chemical-use efficiency, process dependability and process ability to meet a consistent phosphorus level.

Chemistry–

Phosphorus removal by alum addition is basically a chemical precipi .tion process. The reaction between the aluminum ion (Al^{+++}) and the phosphate ion ($PO_4^{\equiv}$) to form the insoluble aluminum phosphate ($AlPO_4$) is shown in Equation 1.

$$Al^{+++} + PO_4^{\equiv} \rightarrow AlPO_4\downarrow \quad (1)$$

The source of aluminum used in this study was a water solution of filter alum, $Al_2(SO_4) \cdot 14H_2O(aq)$. The precipitation process with this chemical is shown in Equation 2. The weight ratio of Al/P is 0.87 g Al/1.0g P (18).

$$Al_2(SO_4)_3 \cdot 14H_2O(aq) + 2PO_4^{\equiv}(aq) \rightarrow 2AlPO_4 + 3SO_4^{=}(aq) + 14H_2O \quad (2)$$

When filter alum is used as the source of aluminum, the weight ratio of alum to phosphorus (Alum:P) is 9.6 kg (22.1 lb) of alum per 1 kg (2.2 lb) of phosphorus. If alum is expressed in terms of Al_2O_3, the theoretical

weight ratio of alum to phosphorus (Alum:P) is 1.64 kg (3.61 lb) of Al_2O_3 per 1 kg (2.2 lb) of phosphorus.

Jar tests were used to determine the Al to P ratio required for a desired residual phosphorus content. These jar tests were performed in accordance with the procedures outlined by the Allied Chemical Corporation (19).

Alum Specifications–

The filter alum used in this study was purchased from the Allied Chemical Corporation and shipped in bulk lots of 15,000 ℓ (4,000 gal) by insulated tank truck. The specifications for liquid alum are shown in Table 3.

TABLE 3. COMPOSITION OF LIQUID ALUM

Weight % as Al	4.37%
Weight % as Al_2O_3	8.3%
Weight % as $Al_2(SO_4)_3 \cdot 14H_2O$	49.0%
Density at 16°C	11.1 lb/gal (1.33 g/ℓ)

Chemical Storage and Handling Equipment–

The storage and handling facilities for the alum shown in Figure 7 were constructed at the study site between August 1975 and September 1976.

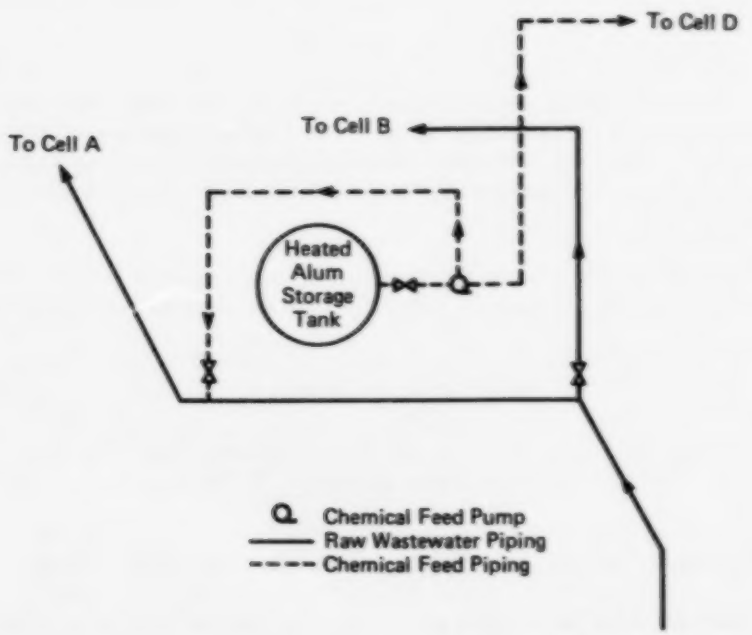

Figure 7. Storage and handling facilities for alum.

An Owens-Corning Fiberglass, insulated tank with electric heater, Model 105M, was installed at the plant site. The tank volume was 18.3 m^3 (4,840 gal). An adjacent building was constructed to house the chemical feed pumps.

Two, BIF Industries Chem-O-Feeder Duplex Chemical Proportioning Diaphragm feed pumps, capacity 1.3×10^{-4} - 1.3×10^{-2} ℓ/sec (0.125 - 12.5 gph), were installed and connected to the chemical storage tank. Calibration curves were prepared to correlate pump stroke setting with chemical output. ABS plastic pipe, 1.90 cm (0.75 in) was used to pipe the alum to the points of addition. This piping was buried in the lagoons to protect it against the cold weather. The addition of alum to the influent of Cell D was done in the chemical contact chamber as shown in Figure 8. The

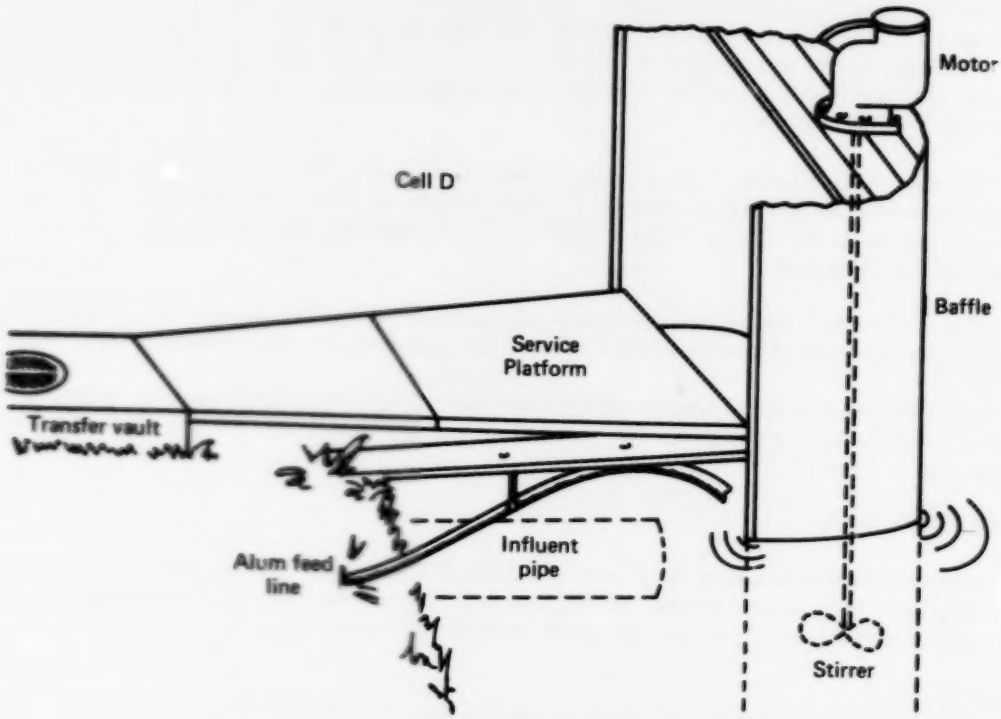

Figure 8. Chemical contact chamber.

chamber was constructed by placing a steel crescent-shaped baffle 0.61 m (2.0 ft) in front of the influent pipe. The Cell D influent and alum were mixed by a variable speed, U. S. Motors mixer Model 095464 mounted on the baffle. A 1.93-m (6.3-ft) shaft and a propeller were connected to the motor. The propeller was located 0.43-m (1.4 ft) from the influent pipe. The feed line was located such that the alum was added to the water surface at a point 0.61 m (2 ft) directly above the propeller. A speed of 550 rpm was used to mix the wastewater and alum.

Alum was added to Cell A through a tap which was installed 61 m (200 ft) upstream from the end of the influent pipe to Cell A. The force main acted as the chemical contact chamber. Chemical contact was effected by the natural turbulence in the force main.

Chemical Addition Process–

Chemical addition to Cell D, the effluent cell, began in September 1976 and continued through August 1977. Bench scale testing of alum, using jar tests, was performed in order to establish the optimum alum concentration to achieve a 1.0 mg/ℓ total phosphorus concentration in the effluent. The results of these tests indicated that a concentration of 32.3 mg/ℓ alum as Al_2O_3 (18.1 mg/ℓ as Al) should be used as the initial concentration for further

testing on the field scale. The determination of the feed rate alum concentration was predicated on a determination of the flow into Cell D. The only true measure of the flow through Cell D was the discharge rate at the pump station, located in the cell. This rate varied as much as 300% on a daily basis as a result of normal operating procedures used by the St. Charles Communities Utilities. Therefore, feed rate calculations were based on the more realistic values obtained from averaging daily effluent flows.

The average flow rate, 1000 m^3/day (0.270 MGD) indicated that the initial feed rate should be 220 mℓ/min in order to achieve the dosage. However, the extreme cold weather in November 1976 caused the effluent pump station and flow meter to be severely damaged. It was therefore impossible to continue using this method at that time. A feed rate of 160 mℓ/min was set based on the achievement of a target effluent concentration for total phosphorus of 1.0 mg/ℓ and the fact that the system had reduced flow during the winter months. The pump station and flow meter were repaired in June 1977 at which point the feed rate remained at 160 mℓ/min. This value produced a 76% removal of total phosphorus.

Chemical addition to Cell A, the influent cell, began in September 1977 and continued through September 1978. Jar tests were again performed to establish the optimum alum concentration to achieve a 1.0 mg/ℓ total phosphorus concentration in the effluent of Cell A (Station 5). The results indicated that a 42.7-mg/ℓ alum as Al_2O_3 (22.6-mg/ℓ Al) should be used.

The chemical feed rate necessary to achieve this concentration was 330 mℓ/min. This was determined by using the average flow value 1220 m^3/day (0.320 MGD) for the prior 12-month period ending in August 1977.

Since this feed rate would have caused an excessive use of alum, 164 mℓ/min were used for the majority of the period. This value gave a consistent (70%) removal of total phosphorus and also was within the theoretical Al:P ratio value of 1.0 to 1.6.

NITRIFICATION STUDY

The study of nitrification of the effluent of a three-cell lagoon started in September 1977 and continued through September 1978. A plastic-media, trickling filter pilot unit was used and operated throughout the study at a recirculation rate of 1:1 and a hydraulic loading of 81.2 ℓ/min/m^2 (2 gpm/ft^2).

Biochemistry—

Nitrification is the two-step, sequential, biological oxidation of ammonia nitrogen, first to nitrites and then nitrates. The two bacterial genera involved are *Nitrosomonas* and *Nitrobacter*.

Nitrosomonas oxidizes ammonia to nitrites according to the reaction shown in Equation 3. The stoichiometric oxygen requirement for nitrification as determined by Stankewich (20) is 4.57 mg O_2/mg NH_4^+ oxidized.

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2H^+ + H_2O \qquad (3)$$

Nitrobacter oxidizes nitrites to nitrates according to the reaction shown in Equation 4.

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- \qquad (4)$$

The reaction carried out by *Nitrosomonas* produces an energy yield of 58-84 kcal per mole of ammonia oxidized (21).

Oxidation reactions by *Nitrobacter* yield 15.4 - 20.9 kcal per mole of nitrate oxidized (21). From an energy standpoint, the higher yielding reaction carried out by *Nitrosomonas* will produce more biomass (cells) than *Nitrobacter* (21).

Parameters Important to Nitrification Activity

The parameters which are important to the physiological and ecological components of nitrification and are, therefore, engineering considerations of the process, include: temperature, ammonia, dissolved oxygen, pH, alkalinity and BOD.

Temperature–

Over a given temperature range which an organism can tolerate, rate processes tend to increase proportionately to increasing temperatures. Generally a 10°C rise in temperature increases a physiological rate by a factor of 2 or 3. This relationship is quite useful for estimating biological performance with respect to different temperatures. When applied to the nitrification process, the estimated rate of NH_4^+ conversion may be estimated over a given temperature range.

Ammonia–

The source from which organisms obtain their energy is an important factor in determining a given population density. Since *Nitrosomonas* obtains energy through the oxidation of ammonia, its population density is thus limited by the availability of ammonia. Nitrites produced by *Nitrosomonas* provide the energy source for *Nitrobactor.* Nitrite concentration is therefore a principle factor determining the population dynamics of *Nitrobactor.*

Dissolved Oxygen–

The oxygen requirement for nitrification is 4.6 mg O_2/mg NH_4^+ oxidized. This ratio is significant when considering the high degree of nitrification that is desired in wastewater treatment systems. An additional oxygen requirement will be imposed on the aquatic environment because of the oxidation of organic matter by heterotrophic bacteria. Since the energy required for nitrifier growth is directly related to the presence of oxygen, it is important that oxygen be provided at least in stoichiometric amounts.

pH and Alkalinity–

Low pH values have been shown to have an inhibitory effect on nitrification (25). During the nitrification process, hydrogen ions are produced which destroy alkalinity at a ratio of 7.14 mg $CaCO_3$/mg NH_4^+-N oxidized to NO_3^-N. It is important that sufficient alkalinity be present to buffer the production of H^+ and insure that the process is not inhibited.

Different investigators have reported varying optimal pH ranges for nitrification (26). A pH range of 7.2 - 8.0 has been estimated as optimal for combined carbon oxidation-nitrification systems; however, this may be conservative when applied to separate state nitrification systems (27). It must be realized that where pH is concerned, most bacteria have the capability to acclimate to changing environments, thus, different optimal pH ranges will be observed.

BOD–

In conventional nitrification systems as well as attached growth nitrification systems, the coexistence of heterotrophic and autotrophic bacteria (nitrifiers) is inherent. Because most systems have a limited surface area upon which bacteria can grow, interspecific competition for this resource occurs. Heterotrophic bacteria oxidize organic material which yields a higher energy value than the nitrification process. This results in a faster growth rate for heterotrophic bacteria. These ecological facts are significant, since the different growth rates of various species will have an effect on the overall species composition of the bacterial population.

BOD constitutes an estimate of the organic material available to heterotrophic bacteria, therefore it is important that this value be relatively low to preclude the competitive exclusion of nitrifying bacteria. A concentration of BOD with regard to nitrogen, which restrains heterotrophic growth, will increase the competitive ability of nitrifiers.

Equipment

A vinyl core, B. F. Goodrich nitrification tower was installed in November 1976. It was located at the southwest corner of the lagoon system, adjacent to Cell F. (See Figure 9) This tower had a cross-sectional area of

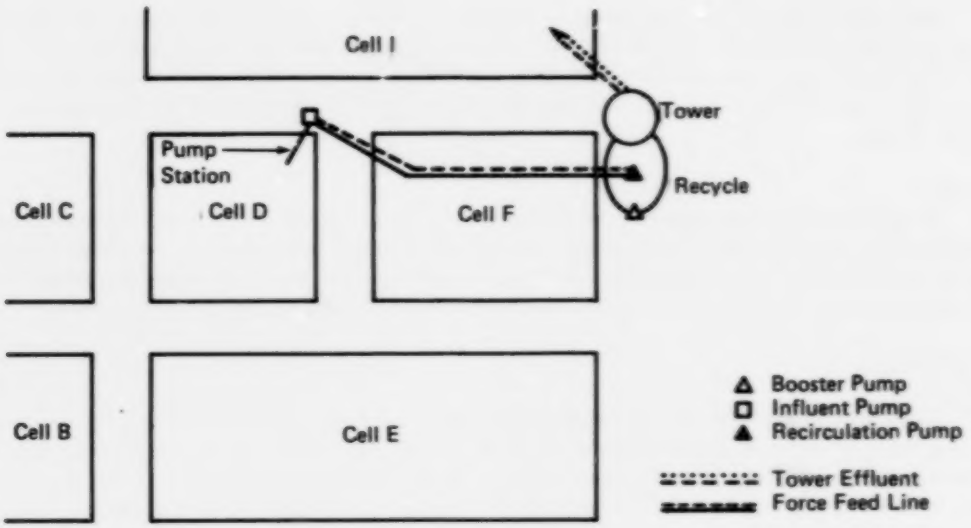

Figure 9. Tower location.

1.2 m^2 (13 ft^2), a media depth of 7.2 m (24 ft), and a media surface area of 99 m^2/m^3 (30 ft^2/ft^3), for a total surface area of 830 m^2 (9200 ft^2). The design hydraulic loading was 20-120 $\ell/min/m^2$ (0.5 - 3.0 gpm/ft^2).

Process Description

The influent for the tower came from the pump station located in the southwest corner of Cell D and was pumped continuously by one, 5.1-cm (2-in), Gorman-Rupp self-priming centrifugal pump. This pump force fed a smaller, 3.8-cm (1.5-in) Gorman-Rupp pump at the base of the tower. The tower influent line was submerged in Cell F in order to protect the line from freezing. Tower recycling was provided by a 3.8-cm (1.5-in), Gorman-Rupp pump at the tower base. Hydraulic flow was measured and controlled by adjusting the head of water flowing through 60° V-notch weirs which were located at the top of the tower. Even distribution over the media was provided by a belt-driven distributor located beneath the weir boxes. There were no facilities provided for the settling and concentration of sludge in either the recycle or effluent stream. Details of the tower piping are shown in Figure 10.

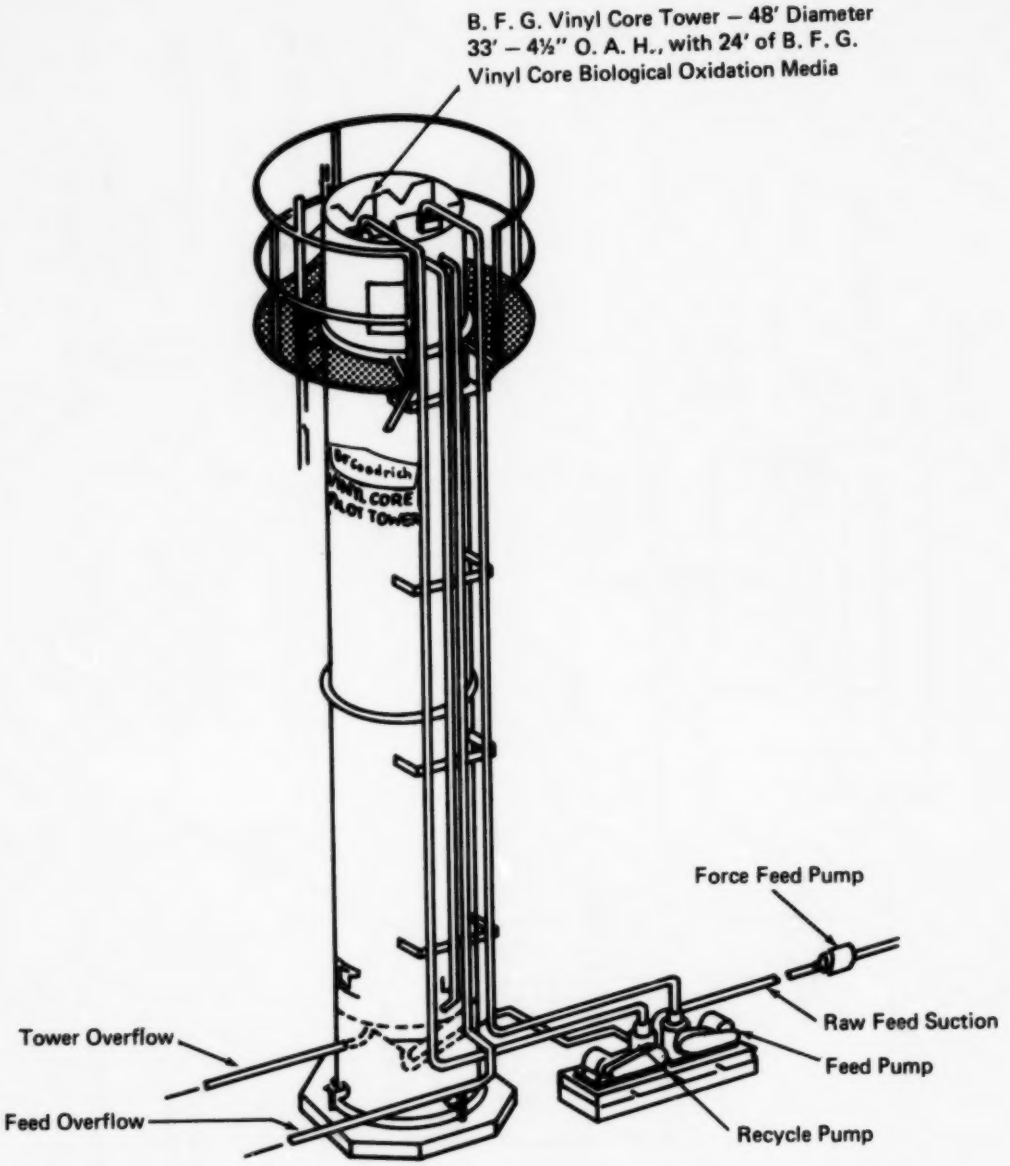
B. F. G. Vinyl Core Tower – 48' Diameter
33' – 4½" O. A. H., with 24' of B. F. G.
Vinyl Core Biological Oxidation Media
Force Feed Pump
Raw Feed Suction
Feed Pump
Recycle Pump
Tower Overflow
Feed Overflow

Figure 10. Tower piping.

The tower system was field tested to determine mechanical dependability at the site. The results of the testing led to the establishment of the hydraulic loading of 6.8×10^{-5} ℓ/s-cm^2 (2 gpm/ft^2) and the recirculation ratio of 1:1, both of which were used during the nitrification study.

SAMPLE COLLECTION AND ANALYSIS

The sampling program was designed to monitor the common influent to the test and control systems, the effluent of each of the three cells in the two systems, and the influent and effluent of the nitrification system.

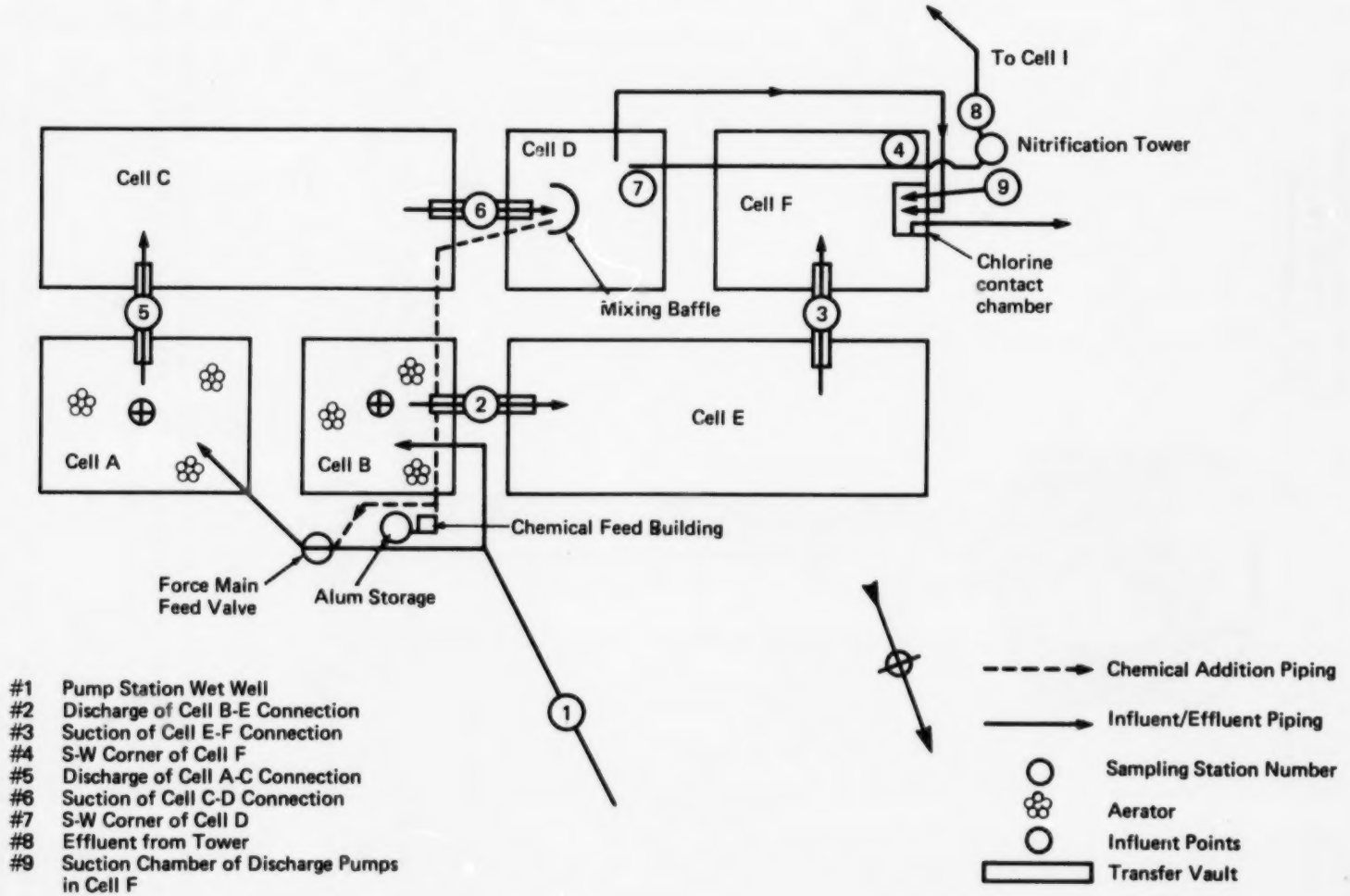

Figure 11. Sampling area with sampling stations.

The sampling stations used in this study are shown in Figure 11. Stations 2, 3, 5, and 6 were located within the transfer vaults connecting the various cells of the lagoon system. Station 7 was located in the southwest corner of Cell D, approximately 1.8 m (6 ft) from the bank between the two test systems' effluent pumps. Station 4 was located in Cell F, approximately 1.8 m (6 ft) from the bank and 0.9 m (3 ft) from the south wall of the chlorine contact chamber. Station 9 was located within the chlorine contact chamber and Station 8 at the tower discharge. Station 1 was located in the wet well of the influent pumping station. The parameters, sample type, sampling location and sampling frequency of the study are shown in Table 4.

TABLE 4. SAMPLING PROGRAM

Parameter	Sample Type	Station 1#	2	3	4	5	6	7	8#	9
Fecal Coliform - count 100/mℓ	G	**			**			**		**
pH - Units	C	*	*	*	*	*	*	*	*	
DO - mg/ℓ	G	*	*	*	*	*	*	*	*	
Alkalinity - mg/ℓ	C	*	*	*	*	*	*	*	*	
Temperature - ^{o}C	C	*	*	*	*	*	*	*	*	
Total BOD_5 - mg/ℓ	C	*	*	*	*	*	*	*	*	
Soluble BOD_5 - mg/ℓ	C	**	**	**	**	**	**	**	**	
TKN - mg/ℓ	C	*	*	*	*	*	*	*	*	
NH_3N - mg/ℓ	C	*	*	*	*	*	*	*	*	
NO_2^-/NO_3^- - mg/ℓ	C	*	*	*	*	*	*	*	*	
Total P - mg/ℓ	C	*	*	*	*	*	*	*	*	
Soluble P - mg/ℓ	C	*	*	*	*	*	*	*	*	
Total Suspended Solids - mg/ℓ	C	*	*	*	*	*	*	*	*	
Volatile Suspended Solids - mg/ℓ	C	*	*	*	*	*	*	*	*	
$SO_4^=$ - mg/ℓ	C	**	**	**	**	**	**	**	**	
Algae Count & Identification	G		**	**	**	**	**	**		
Cl_2 Residual - mg/ℓ	G									**

* M, W, Th

** F

\# All parameters from these stations were measured from grab samples

G Grab sample

C Composite sample

Those samples designated as "composite" were obtained using a Brailsford and Company (Model EVS-1, Series B) automatic effluent sampler, with a 2.3-ℓ glass sample container (see Figure 12). These samplers collected constant volume, at a constant time frequency to obtain a 2-ℓ (2.1-qt) sample in a 24-hour period.

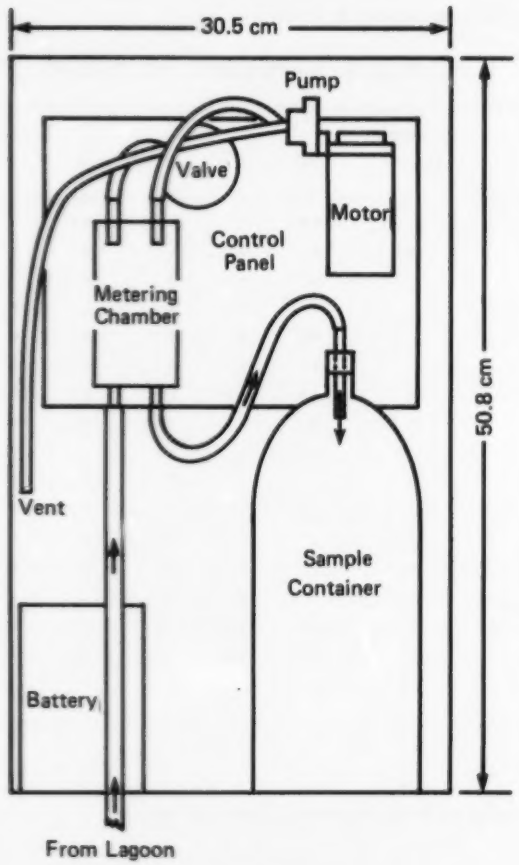

Figure 12. Automatic effluent sampler.

The composite samplers at Stations 2, 3, 5, and 6 were housed in 210-ℓ (55-gal) black steel drums. The drum and sampler were positioned in the manhole of the transfer vault as shown in Figure 13.

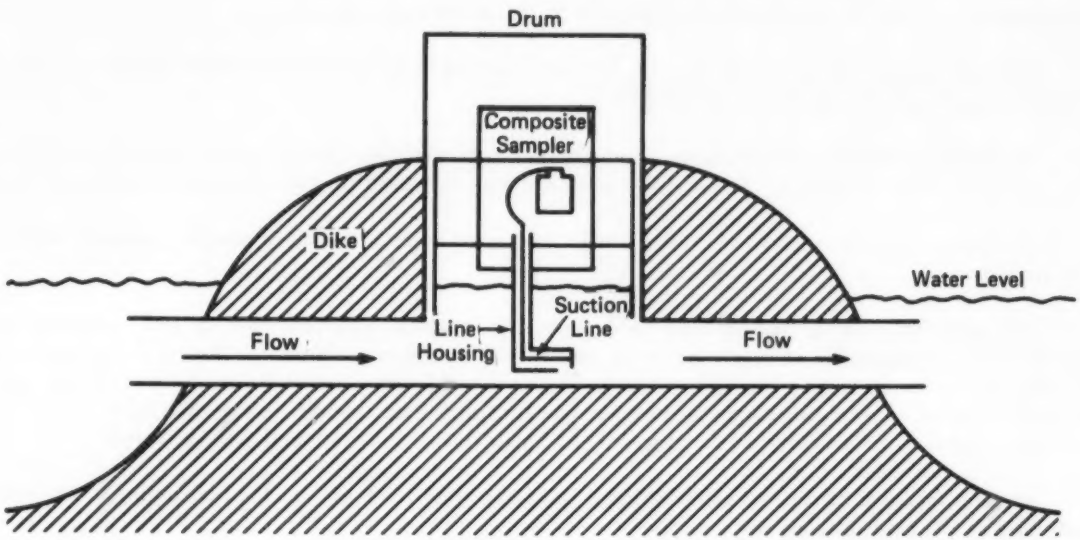

Figure 13. Transfer vault with sampler.

The flexible tygon® suction lines were housed in 1.8-cm (0.75 in), PVC pipe which allowed positioning of the inlet line in a downstream orientation. Composite samples located at Station 4 and 7 were also housed in 210-ℓ (55-gal), black steel drums. These sampler drum units were positioned at the bank of the southwest corner of Cell D and the bank of the west corner of Cell F, respectively. The suction lines were positioned with wooden arms to withdraw samples 1.8 m (6 ft) from the lagoon banks as shown in Figure 14.

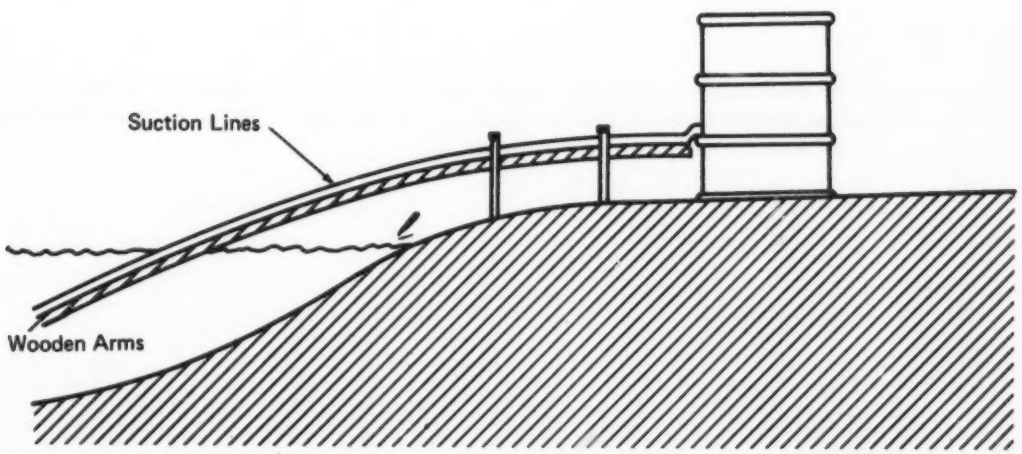

Figure 14. Sampler drum unit.

Grab samples at Stations 2, 3, 5, and 6 were taken from the influent side of the transfer vault. Grab samples from Stations 4, 7, and 9 were collected 0.6 m (2 ft) from the lagoon embankment.

Dissolved oxygen and fecal coliform samples were obtained in separate 300-mℓ BOD bottles. The samples for algae analysis were obtained in 1-ℓ glass bottles.

The samples obtained at Station 1 were grab samples. They were taken from the wet well at this location at a depth of 9.1 m (30 ft) using a 9.5-ℓ (2.5-gal) bucket and were then transferred to closed containers for transport.

All samples from Station 8 were grab samples and were obtained by filling sample containers from the effluent pipe.

The sampling program was modified to accommodate holidays, inclement weather and equipment malfunctions. In those instances when less than three samples were taken during a week, the Monday sampling schedule was followed to insure a minimum of one analysis per week on all parameters. Occasionally when the composite samplers malfunctioned, a grab sample was obtained at the normal grab sample location. During extremely cold periods, the lagoons became covered with ice and all sampling was discontinued until thawing occurred.

At the conclusion of each sampling period, all samples were transported to the laboratories at the College and stored at 4°C until analyses were completed.

ANALYTICAL PROCEDURES AND APPARATUS

All analyses were performed by professional personnel of the Pollution Abatement Technology Department in the laboratories of the Charles County Community College. The laboratories utilized were: the Analytical Laboratory—used for all wet chemical analyses; the Microbiology Laboratory used for the fecal coliform analyses and algae counts; and the Research Laboratory used for the Technicon Autoanalyzer I.

All analyses were performed in accordance with the procedures given in *Standard Methods for the Analysis of Water and Wastewater*, 14th edition, 1975, or the *EPA Manual of Methods for Chemical Analysis of Water and Wastes*, 1974. The methods and the special laboratory equipment used for the measurement of these parameters are outlined in Table 5.

Meteorological Data

Precipitation and air temperature (maximum, average and minimum) were collected at a weather station located in La Plata, Maryland, 16 km (10 miles) from the lagoon site. The information was taken from *Climatological Data*, NOAA, 1975 - 1978. These data are presented in Appendix C.

TABLE 5. METHODS AND SPECIAL LABORATORY EQUIPMENT

Parameter/Units	Method	Equipment	References (Page) Standard Methods*	EPA Manual**
1. Fecal Coliform/ Number per 100 mℓ	MPN	--	922	--
2. pH/pH Units	Electrometric	Fisher Model 140 pH Meter	460	--
3. Dissolved Oxygen/ mg/ℓ	Winkler (Azide Modification), Fixed in the field		--	51
4. Alkalinity/as $CaCO_3$, mg/ℓ	Potentiometric titration to pH 4.5	Fisher Model 140 pH Meter	278	--
5. BOD_5 (Total)/mg/ℓ	Membrane electrode; samples added directly to 300 mℓ BOD bottles	YSI Model 54 Dissolved Oxygen Meter	543	--
6. BOD_5 (Soluble)/ mg/ℓ	Membrane electrode; samples filtered through 934A Reeve Angel glass fiber filters; then added directly to 300 mℓ BOD bottles	YSI Model 54 Dissolved Oxygen Meter	543	--
7. COD (Total)/mg/ℓ	Dichromate reflux; 20 mℓ sample	--	550	--
8. COD (Soluble)/mg/ℓ	Sample filtered through 934A Reeve Angel glass fiber filters; followed by dichromate reflux; 20 mℓ sample	--	550	--
9. TKN/as N, mg/ℓ	Digestion and distillation; followed by automated phenate method	Technicon Autoanalyzer I	--	175 and 182
10. NH_3/as N, mg/ℓ	Automated phenate method	Technicon Autoanalyzer I	--	182

(continued)

TABLE 5. (continued)

Parameter/Units	Method	Equipment	References (Page) Standard Methods*	EPA Manual**
11. NO_2^-/NO_3^-/as N, mg/ℓ	Automated hydrazine reduction	Technicon Autoanalyzer I	Kamphake, L. J., et. al., "Automated Analysis for Nitrate by Hydrazine Reduction," Water Research, Vol. 1, pp. 205 - 216, Pergamon Press, NY, 1967.	
12. Phosphorus (Total)/ as P, mg/ℓ	Persulfate digestion; followed by Automated Ascorbid Acid Reduction	Technicon Autoanalyzer I	474 and 624	--
13. Phosphorus (Soluble)/ as P, mg/ℓ	Filtration with 934A Reeve Angel glass fiber filters; followed by persulfate digestion and the automated Ascorbic Acid Reduction	Technicon Autoanalyzer I	472, 474, and 624	--
14. Suspended Solids (Total)/mg/ℓ	Gooch crucible fitted with 934A Reeve Angel glass fiber filters	Mettler Balance, Model H10T	94	--
15. Suspended Solids (Volatile)/mg/ℓ	Ignition at 550°C	Mettler Balance, Model H10T	95	--
16. Sulfate/mg/ℓ	Sample filtration with 934A Reeve Angel glass fiber filters; followed by turbidimetric determination with Hach Chemical Company SulfaVer IV reagent	Hach Chemical Company Turbidimeter Model 2100A	496	--
17. Algae/organisms per mℓ	Fixing by merthiolate treatment; concentration by sedimentation; counting by Palmer-Maloney counting cell	Bausch & Lomb, Series B, Flat field microscope	1018 and 1024	--
18. Chlorine Residual/mg/ℓ	Orthotolidene by Hach Colorimeter	Hach Chemical Company Colorimeter	--	--
19. Temperature	Measured in the field	--	--	--

* Standard Methods for the Examination of Water and Wastewater, 14th Ed., 1975
** EPA Manual of Methods for Chemical Analysis of Water and Wastes, 1974

DATA ANALYSIS

All data from the project were entered in an IBM 5100 portable computer. The monthly averages of the chemical and microbiological analyses are presented in Appendix A, by station. The results shown in Appendix B give the high, average and low values, as well as the standard deviation for each parameter at each station. The geometric mean has been calculated for specific parameters and is also shown in the Appendices.

ALGAE ANALYSIS

The identification and enumeration of algae were conducted in an effort to establish the phytoplankton dynamics of the lagoon system. Knowledge of algal populations, both quantitatively and qualitatively, is important for several reasons: 1) Photosynthetic activity of algae provide a major portion of the oxygen necessary for aerobic degradation of organic matter in facultative lagoons; 2) algae maintain an important link in the food chain of lagoon ecosystems; 3) during certain periods, algae constitute a major portion of suspended organic solids and 4) algae play an important role in maintaining certain amounts of nutrients in the lagoon system.

SAMPLE COLLECTION

Phytoplankton samples were collected at Stations 2 - 7 (see Figure 11). Sampling was initiated October 7, 1977 and continued on a weekly basis through September 29, 1978. One-liter grab samples were obtained 23 cm (9 in) below the surface in 1300-mℓ glass bottles. The sample temperature was determined immediately and each sample was tagged. Samples were preserved by adding 36 mℓ of merthiolate fixative to the sample bottles (22). Each sample was stored at 4°C and concentrated by the sedimentation technique (23). Resulting concentrations ranged from 10 - 25 mℓ.

EXAMINATION

Phytoplankton samples were examined with a flat-field binocular microscope. A preliminary examination was performed at 1000 X to precisely identify each form by genera. After each preliminary examination, enumeration was performed at 400 X using a Palmer-Maloney counting cell and whipple eye-piece micrometer. Twenty fields were examined from each sample. All counts were made as clump counts by which each naturally occurring single filamentous, colonial or single cell organism was scored as one unit. The number of units/mℓ was calculated given the area of the counting cell, volume of original sample, the volume of sample concentrate, the number of fields counted and the area of whipple grid (23). Clarification and identification were according to Prescott (24). A complete listing of the algae identified by genera and estimated densities is provided in the discussion section.

SECTION 6

RESULTS AND DISCUSSION

BACKGROUND DATA STUDY

The first task of the project was to gather operational data over a 3-year period on a three-cell lagoon system. Cells B, E, and F were referred to as the "control" cell systems. Monthly averages for all sampling stations are presented in the Appendices (A and B). Yearly and 3-year averages for each parameter of the control system are presented in Table 6.

TABLE 6. CONTROL LAGOON SYSTEM YEARLY AVERAGES*

	Alk	BOD Tot	BOD Sol	COD Tot	COD Sol	TKN	NH_3N	NO_2^-/NO_3^-	Phosphorus Tot	Phosphorus Sol	Suspended Solids	$SO_4^=$
Station 1												
First Year	180	160	77	307	163	17.8	13.3	.28	9.6	8.1	134	47
Second Year	192	177	89	396	211	22.4	20.7	.24	15.1	11.1	147	58
Third Year	202	118	60	352	159	27.4	26.6	.27	9.6	7.5	145	45
Three Yr. Avg.	192	149	73	349	174	23.4	20.4	.26	10.6	8.7	142	49
Station 2												
First Year	158	28	11	119	57	13.3	9.5	.22	8.0	7.1	52	21
Second Year	166	30	10	172	71	13.8	11.0	.21	9.4	8.1	77	35
Third Year	157	28	11	161	76	15.5	13.6	.77	6.6	5.3	63	41
Three Yr. Avg.	160	29	11	148	68	14.4	11.4	.4	7.9	6.7	63	32
Station 3												
First Year	152	23	10	100	53	10.9	9.0	.39	7.7	6.8	42	19
Second Year	161	25	8	120	60	11.5	9.1	.24	9.0	8.2	46	31
Third Year	136	18	5	103	99	10.1	8.6	.50	5.9	5.0	40	34
Three Yr. Avg.	147	22	7	107	53	10.7	8.9	.38	7.4	6.5	42	28
Station 4												
First Year	146	25	10	107	53	9.3	7.4	.42	7.2	6.5	45	22
Second Year	149	21	7	112	55	9.1	6.9	.32	8.3	7.3	43	33
Third Year	122	14	5	88	50	7.6	6.1	.47	4.8	4.1	31	37
Three Yr. Avg.	138	20	7	101	52	8.5	6.8	.40	6.6	5.8	39	30

*Units of all parameters are in mg/ℓ.

The control lagoon was studied to determine if a three-cell lagoon system could meet the secondary treatment standards of 30-mg/ℓ BOD; suspended solids as well as the 200 MPN/100 mℓ standard for fecal coliform

concentration in the effluent. Two-cell and one-cell systems were also examined. In addition, the effects of lagoon treatment on nitrogen as measured by total Kjeldahl Nitrogen (TKN), ammonia nitrogen (NH_3/N) and nitrite/nitrate nitrogen (NO_2^-/NO_3^-) were examined. The natural reduction of total phosphorus and soluble phosphorus through the system was also analyzed.

Biochemical Oxygen Demand (BOD)

The monthly averages for the overall lagoon influent and Stations 2, 3, and 4 (Cells B, E, F) effluent for BOD are presented graphically in Figures 15, 16, and 17, respectively.

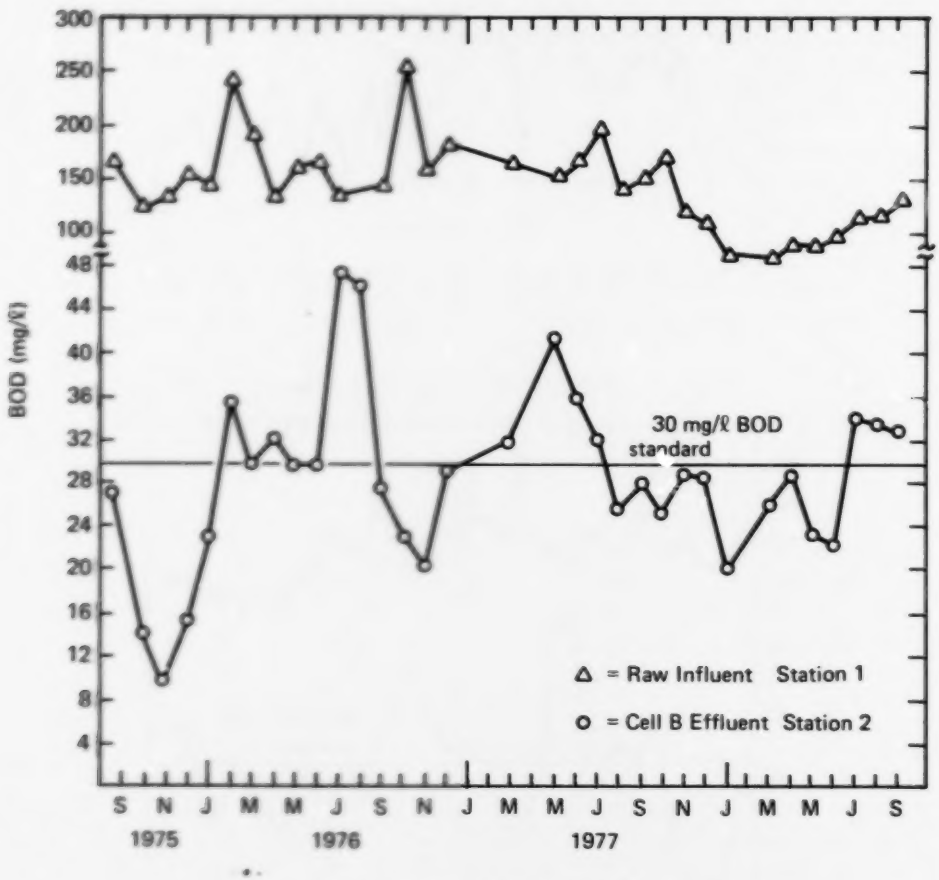

Figure 15. BOD, raw influent and Cell B effluent.

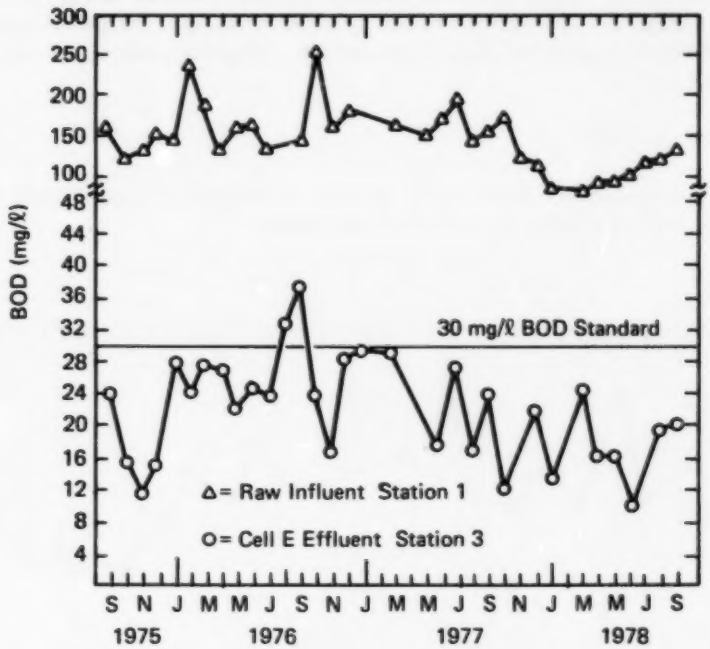

Figure 16. BOD, raw influent and Cell E effluent.

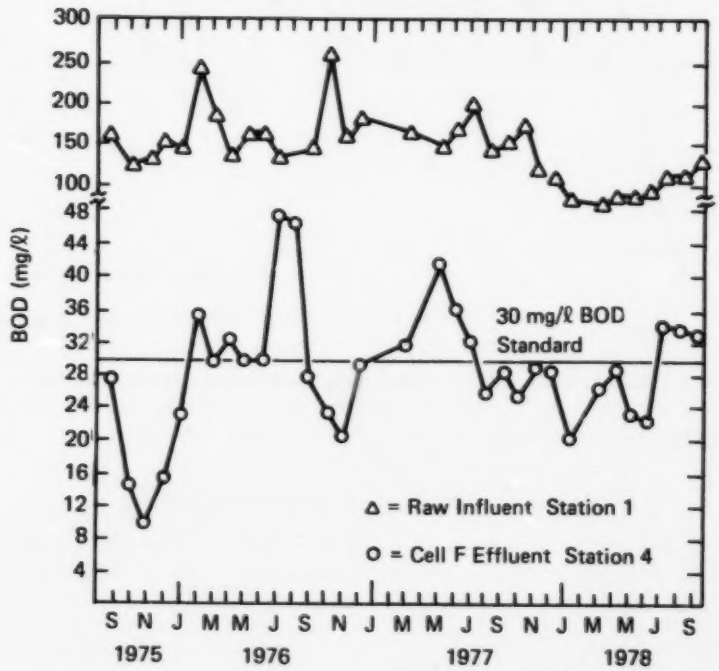

Figure 17. BOD, raw influent and Cell F effluent.

The BOD standard of 30 mg/ℓ was met 66% of the time for Cell B, 92% of the time for Cell E and 86% of the time for Cell F. This is on a monthly basis for the entire period of study. On a yearly basis, BOD removal is more consistent for Cells E and F.

A further evaluation of the control system, as shown in Figure 18, indicates that there is a 92% probability that a three-cell system will meet the 30-mg/ℓ BOD standard. A two-cell system will meet the standard 92% of the time, while a one-cell system will only meet the standard 63% of the time.

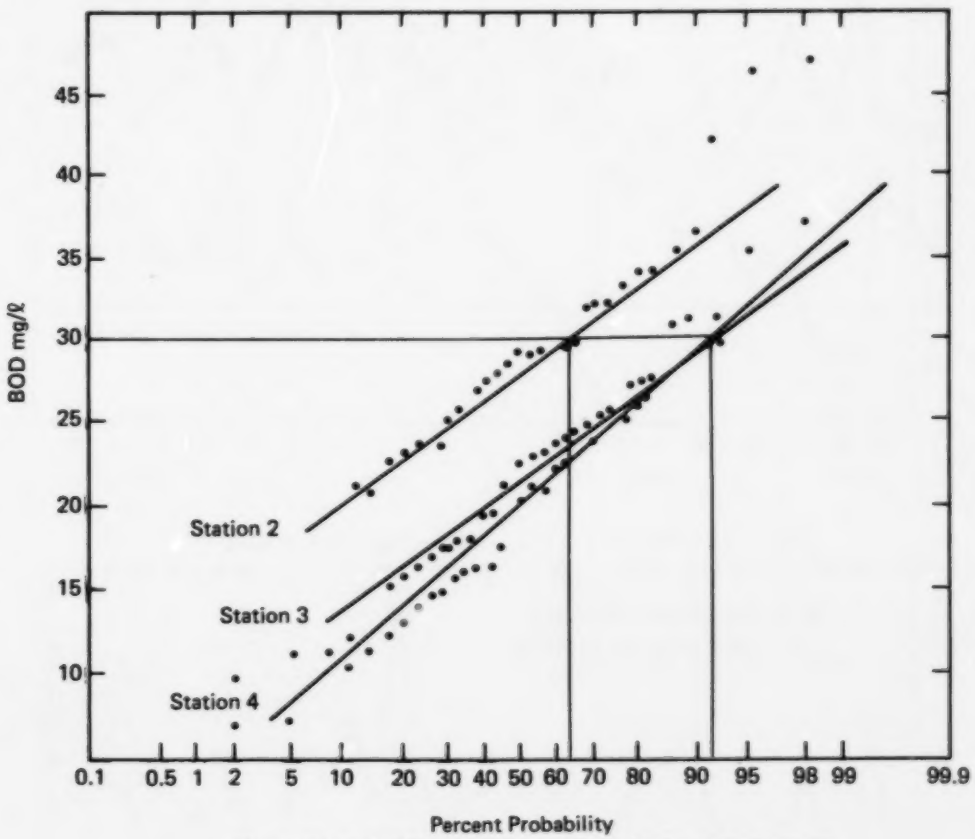

Figure 18. Probability of BOD remaining in the control system.

It can be concluded from the data that a two-cell lagoon system whose first cell is aerated will meet existing EPA effluent limitations for BOD. For the period during which this study was conducted, the percent removal BOD for the first cell was 81%, for the first two cells it was 86%, and for the overall control system it was 87%. On this basis, there appears to be no justification for the third cell. In fact, the value of the second cell is questionable. The soluble BOD concentration in the influent system was 49% of the total BOD over the period of the study. The soluble BOD for the effluent of Cells B, E, and F was 37%, 33%, and 33%, respectively. From this it may be concluded that the majority of soluble BOD is converted to insoluble BOD in the first cell of the system and that little conversion of soluble BOD to insoluble BOD occurs in the second and third cells.

Suspended Solids

The raw influent and cell effluent suspended solids monthly averages for Stations 2, 3, and 4 (Cells B, E, and F) are presented graphically in Figures 19, 20, and 21, respectively.

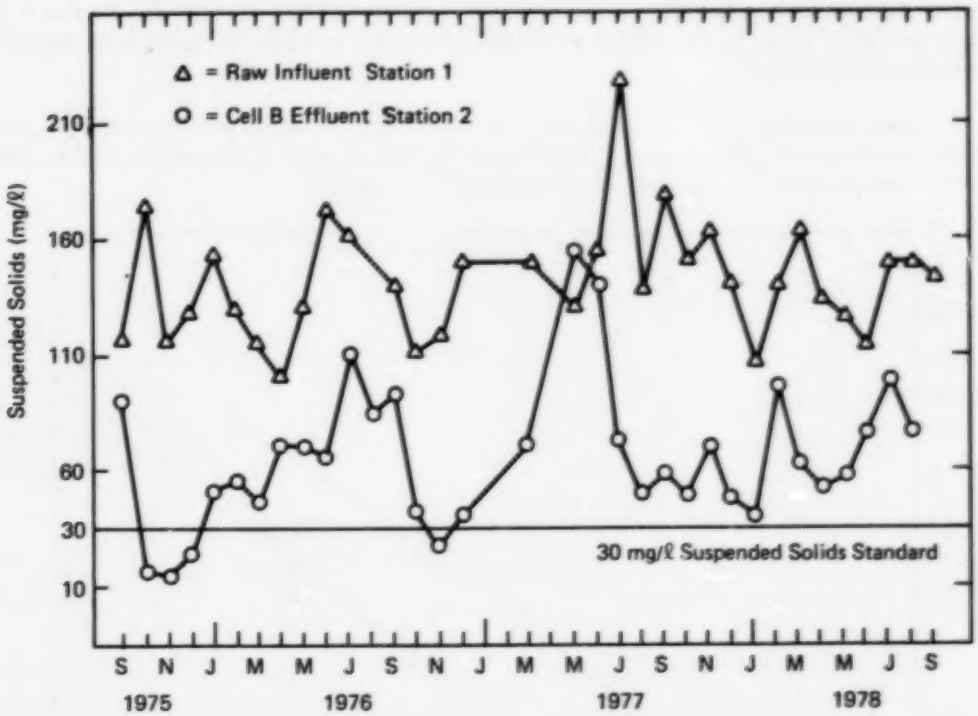

Figure 19. Suspended solids, raw influent and Cell B effluent.

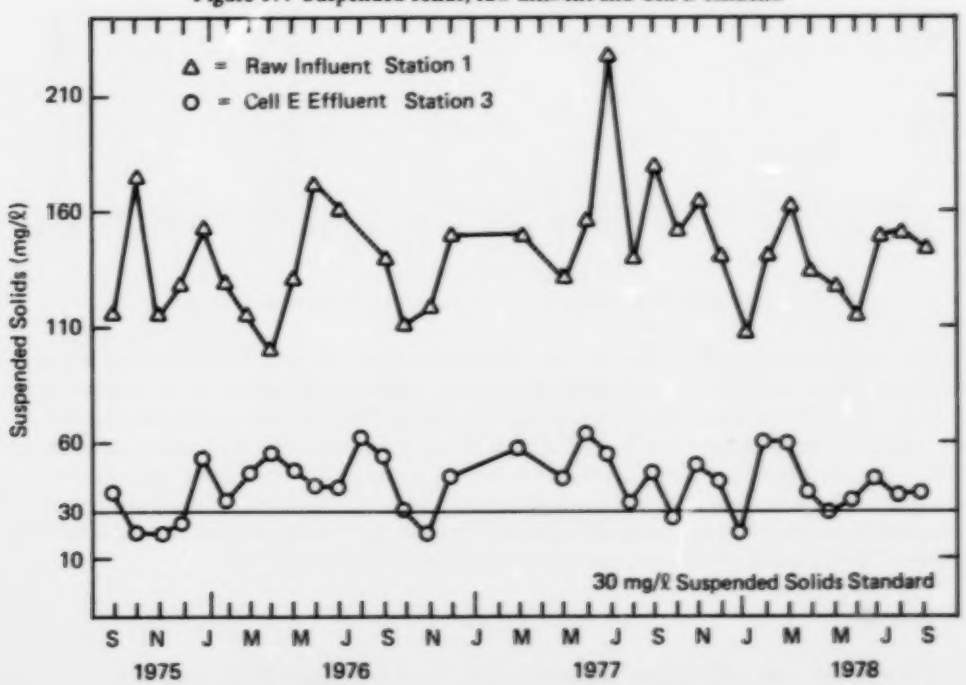

Figure 20. Suspended solids, raw influent and Cell E effluent.

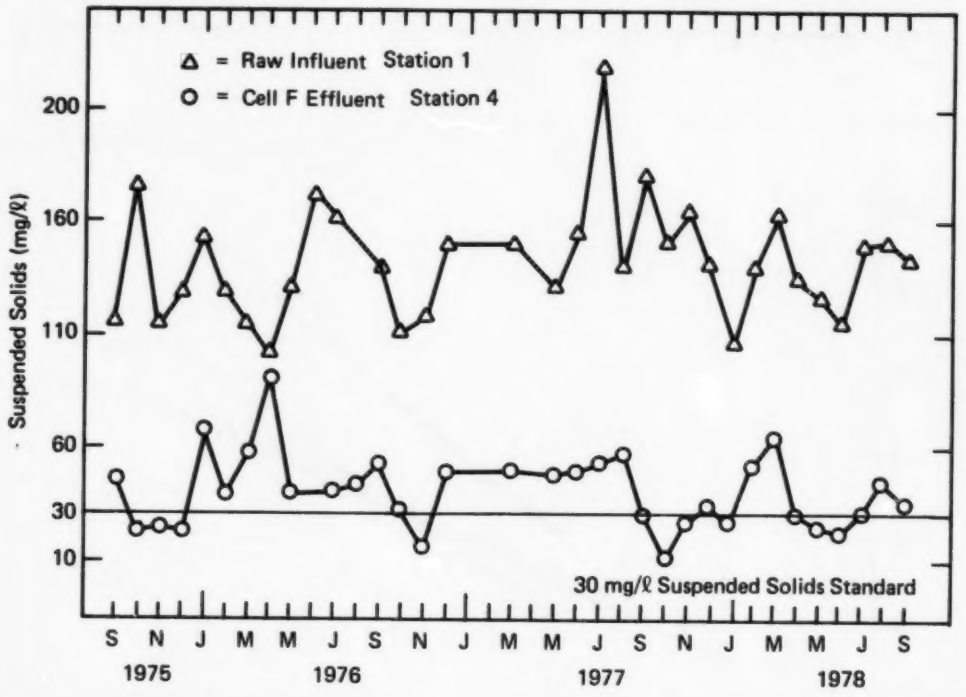

Figure 21. Suspended solids, raw influent and Cell F effluent.

The suspended solids standard of 30 mg/ℓ was met 12% of the time for Cell B, 18% of the time for Cell E, and 30% of the time for Cell F. This is based on a monthly average for the entire study.

The percent removal of suspended solids for the first cell was 63%; for the first two cells was 70%, and for the overall control system it was 73%.

A further evaluation of the control system as shown in Figure 22, indicates that there is a 34% probability that a three-cell system will meet the 30-mg/ℓ suspended solids standard. A two-cell system will meet the standard 22% of the time, while a one-cell system will only meet the standard 12% of the time.

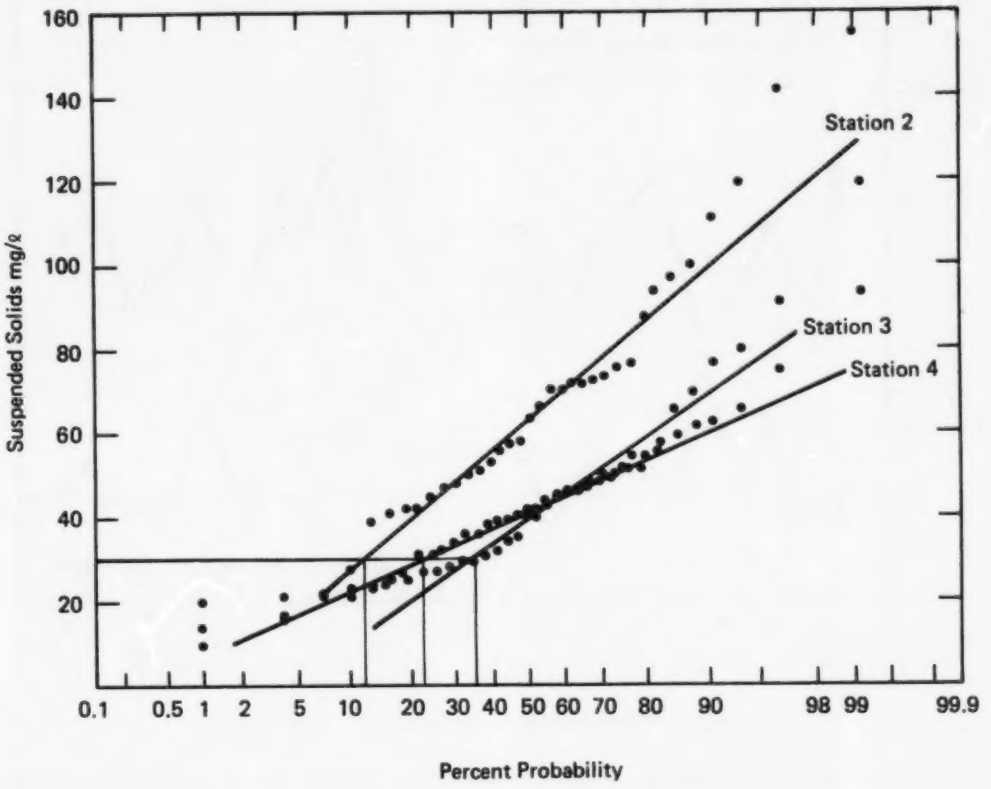

Figure 22. Probability of suspended solids removal in the control system.

The 3-year average of percent volatile suspended solids in the influent was 81%. Cells B, E, and F had 3-year percent volatile solids averages of 86%, 87%, and 84%. Due to the nature of this system, the variation in percent volatile solids can most likely be attributed to the algae populations which increase and decrease with seasonal changes.

From this data, the suspended solids standard of 30 mg/ℓ was not met over the 3-year period by either a single, two-cell, or three-cell lagoon system. The average removal efficiency between the second cell (Cell E) and the third cell (Cell F) was only increased from 70% to 73%.

In view of the BOD data previously presented, the third cell of this three-cell system has limited value in reducing the second cell's effluent to secondary standards for BOD and suspended solids.

At the time this report was being prepared, the state of Maryland had raised the suspended solids standards on lagoons to 90 mg/ℓ in the effluent (33). Considering this new standard, it can be shown that the effluent from a two-cell system would meet the local state's suspended solids standard consistently. A one-cell aerated system would still remain questionable.

Fecal Coliform

The fecal coliform values for the control and test systems are shown in Appendix D.

The 3-year geometric mean of the fecal coliform count in the influent was 7.6 X 10^8 MPN/100 mℓ. The 3-year average geometric mean of the fecal coliform count in the unchlorinated effluent of Cell F was 1.5 X 10^3 MPN/100 mℓ. Only 15% of the samples analyzed on the unchlorinated effluent of Cell F were below 200 MPN/100 mℓ. The geometric mean of the fecal coliform count in the chlorinated effluent was 5 MPN/100 mℓ. Chlorination of Cell F effluent resulted in a log reduction in the influent of 6, compared to a log reduction of 3 for the unchlorinated effluent.

It can be concluded that a reduction of fecal coliform organisms occurs in a three-cell lagoon system, a level of 200 MPN/100 mℓ for fecal coliform cannot be achieved without chlorination of the effluent.

Nitrogen

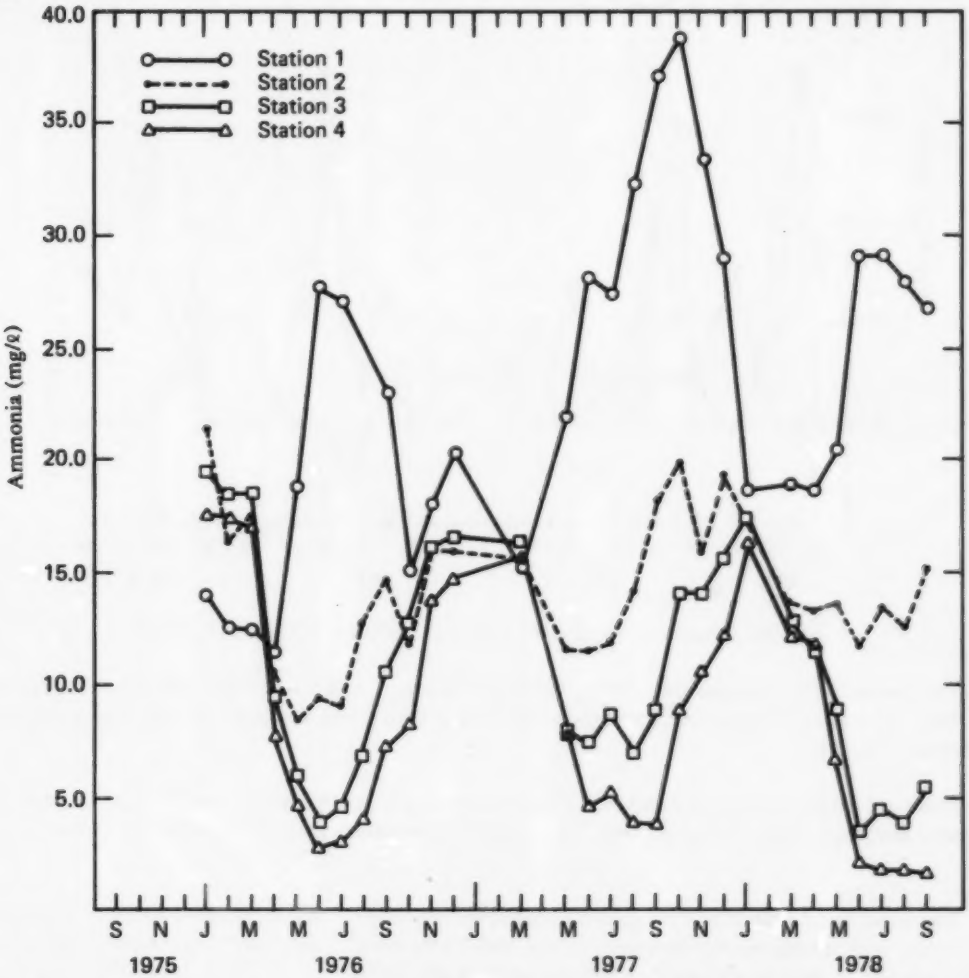

Figure 23. Ammonia of raw influent and effluent for Cells B, E, and F (Stations 1, 2, 3, and 4).

Figure 23 graphically presents 3-year data on the ammonia concentrations of the raw influent and the effluent for Cells B, E, and F (sample Stations 1, 2, 3, and 4, respectively).

Cell B had a 3-year ammonia average reduction of 44%. Cells E and F had a 3-year average reduction of 22% and 24%, respectively. The higher reduction occurring in the first cell (Cell B) can be attributed to the aeration of that cell, and the larger amounts of nitrogen available for utilization by bacteria.

The two-cell system (Cells B and E) had an overall 3-year removal efficiency of 56%, while the complete three-cell system had an overall removal efficiency of 67% for the 3-year period. The trend for TKN concentration shows a similar pattern.

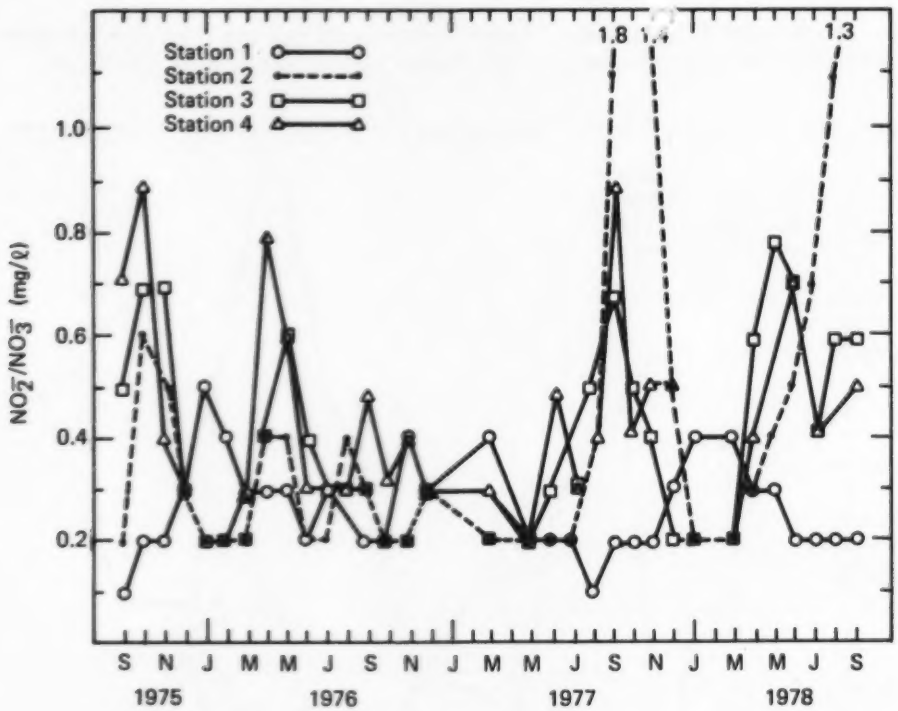

Figure 24. Nitrate/nitrite of raw influent and effluent of Cells B, E, and F.

The nitrite/nitrate nitrogen (NO_2^-/NO_3^-) data for Cells B, E, and F is presented in Figure 24. The majority of NO_2^-/NO_3^- formation occurs in Cell B and then decreased in Cells E and F. Again, this behavior can be attributed to the aeration of Cell B.

From the nitrogen data presented, the effluent ammonia is much lower during the summer months, indicating greater microbial action during this time. The winter months have higher values indicating a reduced biological activity.

The aeration of Cell B has the greatest impact on reducing the ammonia concentration, while increasing the NO_2^-/NO_3^- concentrations. Furthermore, Cells E and F have no effect on increasing the NO_2^-/NO_3^- concentration, although they provide an approximate 40% reduction in ammonia.

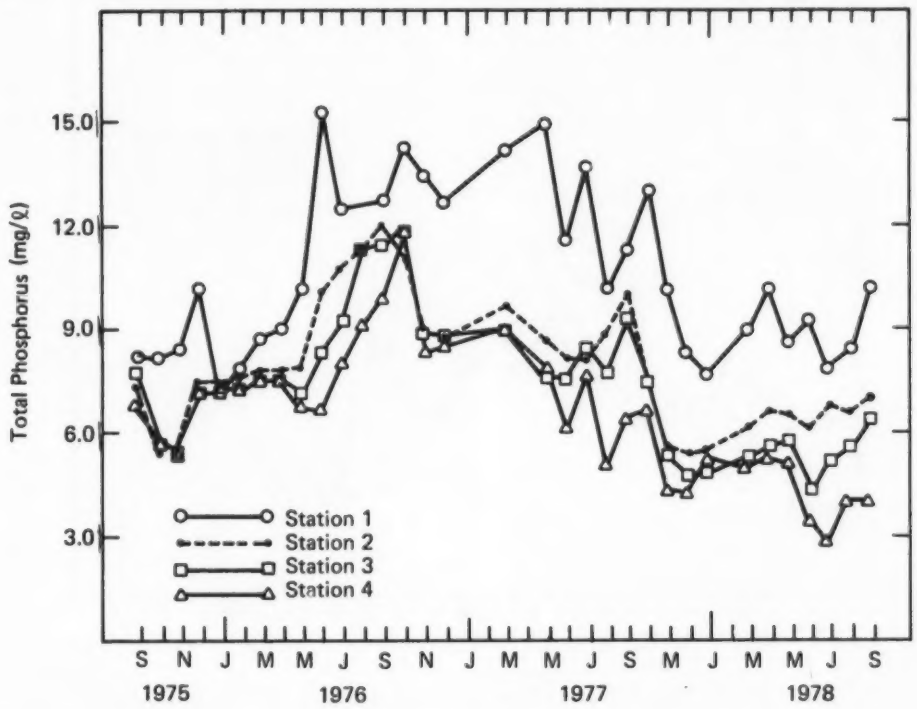

Figure 25. Total phosphorus concentrations of raw influent and effluent of Cells B, E, and F.

The total phosphorus concentration for the test system at Stations 1, 2, 3, and 4 is presented in Figure 25.

Utilizing average concentrations for three years, it can be seen that the phosphorus concentration was reduced by 25%, 6%, and 11% for Cells B, E, and F, respectively. The two-cell system of B and E had a reduction of 30%, while the three-cell system had an overall reduction of 38%.

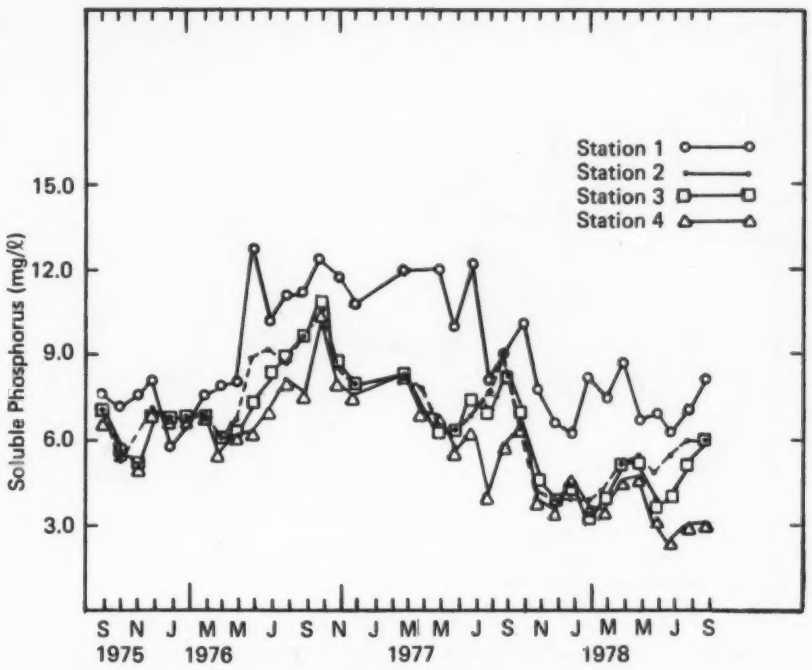

Figure 26. Soluble phosphorus of raw influent and effluent of Cells B, E, and F.

The soluble phosphorus data for the 3-year study period is presented in Figure 26. Cells B, E, and F (Stations 2, 3, and 4) had phosphorus reductions of 22%, 3%, and 11%, respectively, over the 3-year period. The first two cells had a 3-year average reduction of 24%, while the three-cell lagoon system had an average reduction of 33%. These reduction rates are lower than the total phosphorus reductions. Soluble phosphorus accounts for 81% of the total phosphorus in the influent. After passing through Cell B, the soluble becomes 84% of the total phosphorus. It becomes 87% of the total phosphorus in Cell E and remains constant at 87% after Cell F.

PHOSPHORUS STUDY

Test System and Control System Comparability

In order to determine the effectiveness of the phosphorus removal process by the addition of alum in situ, the experimental method required that the results from the test system be compared to the sister control system operating in parallel. The assumption was that the control system would reflect the baseline operation of the test system and thus, the effect of alum addition on phosphorus concentrations could be differentiated from normally occurring variations in the phosphorus concentration.

The similarity of the test system, Cells A, C, and D, and the control system, Cells B, E, and F, was tested during the first year of the project, September 1976 to September 1977, and the data was analyzed on two bases: 1) removal efficiencies across sister cells within the two systems (A - B, C - E, and D - F), and across the entire system, and 2) water quality at sister sampling points in the two systems (2 and 5, 6 and 3, and 7 and 4) as shown in Figure 27.

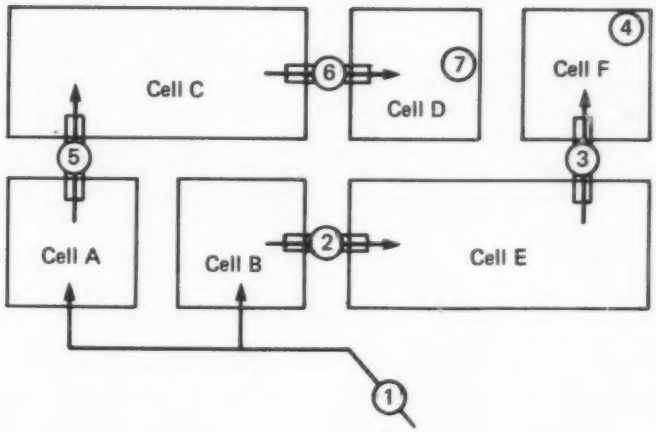

Figure 27. Test and control systems.

The two-cell system of A - C and B - E operated with comparable efficiency as shown in Table 7.

TABLE 7. SYSTEM A - C AND B - E COMPARISON (% EFFICIENCY)

	BOD		COD			Phosphorus		Suspended
	Tot	Sol	Tot	Sol	NH_3N	Tot	Sol	Solids
System B - E	86	87	67	69	32	20	16	69
System A - C	85	87	68	70	44	21	12	69

The efficiency of Cell D was less than Cell F as shown in Table 8.

TABLE 8. CONTROL SYSTEM AND TEST SYSTEM (% EFFICIENCY)

	BOD		COD			Phosphorus		Suspended
	Tot	Sol	Tot	Sol	NH_3.	Tot	Sol	Solids
Control	84	88	65	68	44	25	20	67
Test	74	82	50	62	38	24	24	46

The water quality at sister sampling points 5 - 2, 6 - 3, and 7 - 4, was measured in terms of total BOD, total COD, suspended solids, total phosphorus, and soluble phosphorus. The data from the sister sites were compared statistically using a t-test to establish the degree of similarity. The statistical analysis showed that there was no difference in the water quality at Stations 5 and 2, and 6 and 3. However, the water quality at Stations 7 and 4 was significantly different. The water quality at Station 7 was significantly poorer than at Station 4. This result, coupled with the lower efficiency in Cell D, indicated possible abnormal conditions in Cell D.

The lagoon site was inspected for possible causes of the low performance of Cell D. A valve on a force

main which fed Cell D was found to be leaking raw wastewater into Cell D. The valve could not be repaired without major construction. In May 1978 the force main with the defective valve was plugged.

As a result of the comparability studies, the data from the chemical addition studies during the second and third years of the project will be evaluated differently. The effects of chemical addition to Cell D during the second year will be evaluated by comparison of second-year data to the baseline data from the test system obtained during the first year of the project. The effects of chemical addition to Cell A during the third year will be evaluated in two ways, 1) by examination of data obtained from the test system during all three years of the project, and 2) by comparison to third-year data from the control system for sister Cells B and E.

Second Year Chemical Addition

The yearly and 3-year averages for each parameter of the test system are presented in Table 9.

TABLE 9. TEST LAGOON SYSTEM YEARLY AVERAGES*

Year/ Station No.	Alk	BOD Tot	BOD Sol	COD Tot	COD Sol	TKN	NH_3N	NO_2^-/NO_3^-	Phosphorus Tot	Phosphorus Sol	Suspended Solids	$SO_4^=$
Station 1												
First Year	180	160	77	307	163	17.8	13.3	0.28	9.6	8.1	134	46
Second Year	192	177	89	396	211	27.4	20.7	0.24	13.1	11.0	147	58
Third Year	202	118	60	352	159	27.4	26.6	0.27	9.6	7.5	145	44
Three Yr. Avg.	192	149	73	349	174	23.4	20.4	0.26	10.6	8.7	141	48
Station 5												
First Year	169	31	12	128	58	12.0	10.1	0.27	8.2	7.3	54	19
Second Year	159	27	9	137	67	12.5	9.8	0.30	8.3	7.1	51	42
Third Year	131	28	8	158	64	16.4	13.6	0.39	3.8	1.9	75	86
Three Yr. Avg.	152	29	9	142	62	14.0	11.3	0.30	6.6	5.3	61	49
Station 6												
First Year	154	24	10	97	49	9.9	7.5	0.49	7.6	7.1	41	18
Second Year	142	24	7	114	56	10.5	8.2	0.24	7.2	6.3	41	54
Third Year	116	19	5	111	53	9.3	7.7	0.57	3.6	2.8	45	77
Three Yr. Avg.	137	22	7	106	52	9.8	7.8	0.43	6.1	5.3	42	47
Station 7												
First Year	138	41	14	152	61	12.5	8.2	0.16	7.3	6.1	72	35
Second Year	86	31	12	104	56	15.5	13.9	0.16	2.5	1.6	32	142
Third Year	117	26	9	136	68	9.4	8.1	0.75	4.1	3.2	41	67
Three Yr. Avg.	116	33	11	178	62	12.1	9.7	0.36	4.8	3.8	53	75

*Units of all parameters are in mg/ℓ.

During the second year, the raw influent was a slightly stronger waste than the first year as measured by BOD, COD, NH_3N, $SO_4^=$ and suspended solids parameters. During chemical addition to Cell D, Cells A and C operating efficiencies were similar to their efficiencies during the first year. The water quality produced by Cells A and C was not significantly different from the water quality produced by sister Cells B and E during the same time period, which can be seen by reviewing Tables 7 and 8.

During periods of low or zero effluent discharge rates, alum which was being added to Cell D at the C - D transfer vault would leak back to Cell C. This was caused by the fact that there was no significant hydraulic head loss between the two lagoon cells to prevent water movement from Cell D to Cell C.

BOD and Suspended Solids

For the year prior to chemical addition in Cell D, the BOD concentration at Station 7 averaged 41 mg/ℓ. The average BOD concentration during chemical addition was 31 mg/ℓ representing a 25% reduction over the previous year.

The BOD and suspended solids values are presented graphically in Figure 28. The baseline suspended solids concentration in the effluent of Cell D (Station 7) was 72 mg/ℓ. The average suspended solids concentration during chemical addition was 32 mg/ℓ, representing a 55% reduction. The increased BOD values can be attributed to the defective valve and in fact, extrapolation of six months of data during the third year shows that the BOD standard of 30 mg/ℓ would have been met.

Data shows that the suspended solids standard of 30 mg/ℓ would not be met, but the 90-mg/ℓ standard would be met consistently. Similar behavior was shown to exist in the control system.

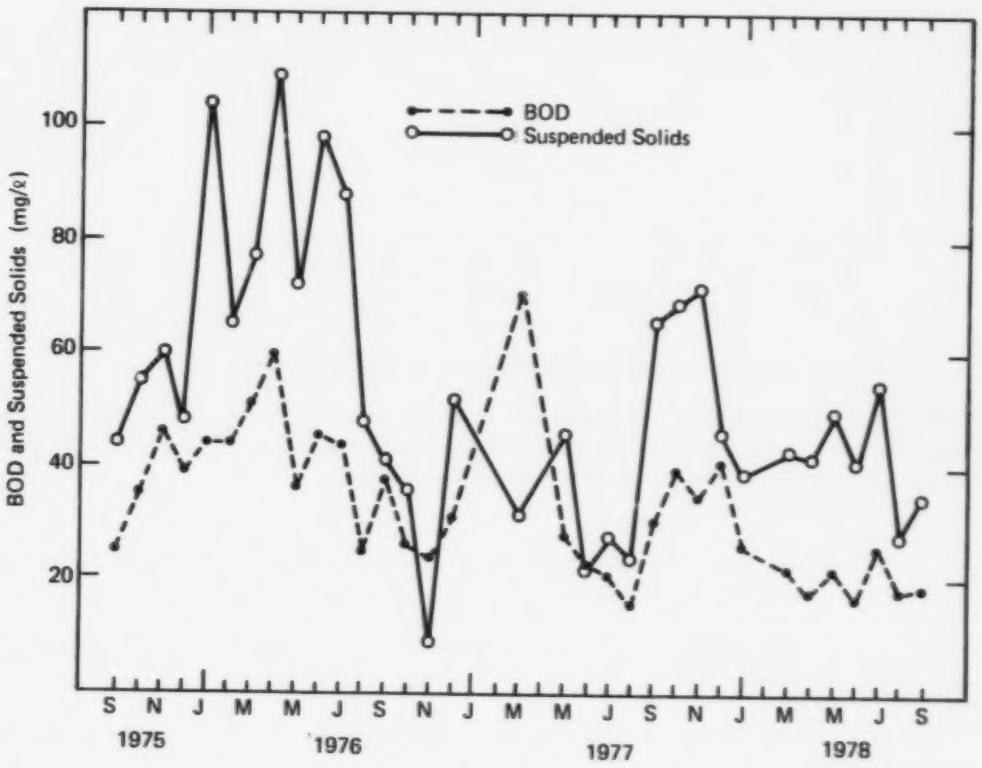

Figure 28. BOD and suspended solids of Cell D (Station 7).

Nitrogen

Figure 29 represents the ammonia concentration for the test system.

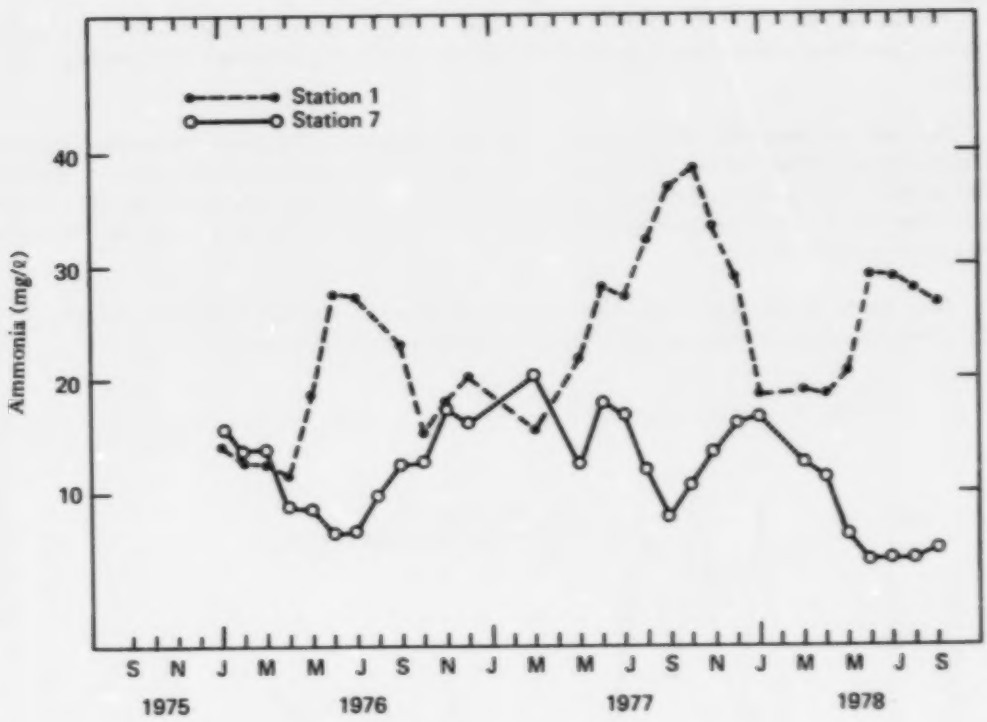

Figure 29. Ammonia of raw influent and effluent of Cell D.

The ammonia concentration increased in the effluent of Cell D during chemical addition. For the year prior to alum addition, the average ammonia concentration in the effluent was 8.2 mg/ℓ. During alum addition, this value increased to 13.9 mg/ℓ. There are several possible causes for this increase:

1. The increased organic matter caused by the addition of alum resulting in an increase in anaerobic decomposition; and
2. The acidic condition present in the cell during alum addition causing a higher NH_4^+ concentration.

Phosphorus

Figures 30 and 31 represent the total phosphorus and soluble phosphorus concentrations, respectively, for the test system (Cell D).

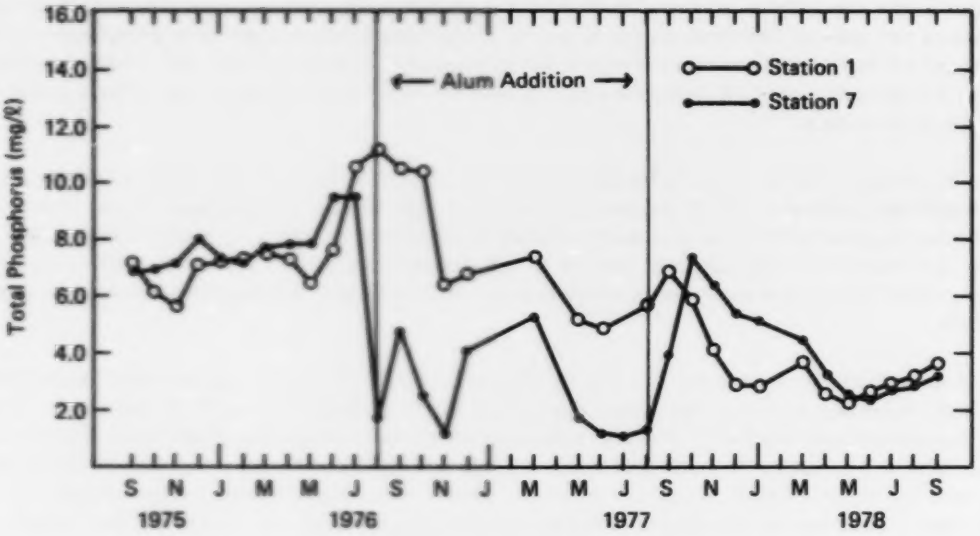

Figure 30. Total phosphorus of raw influent and effluent of Cell D.

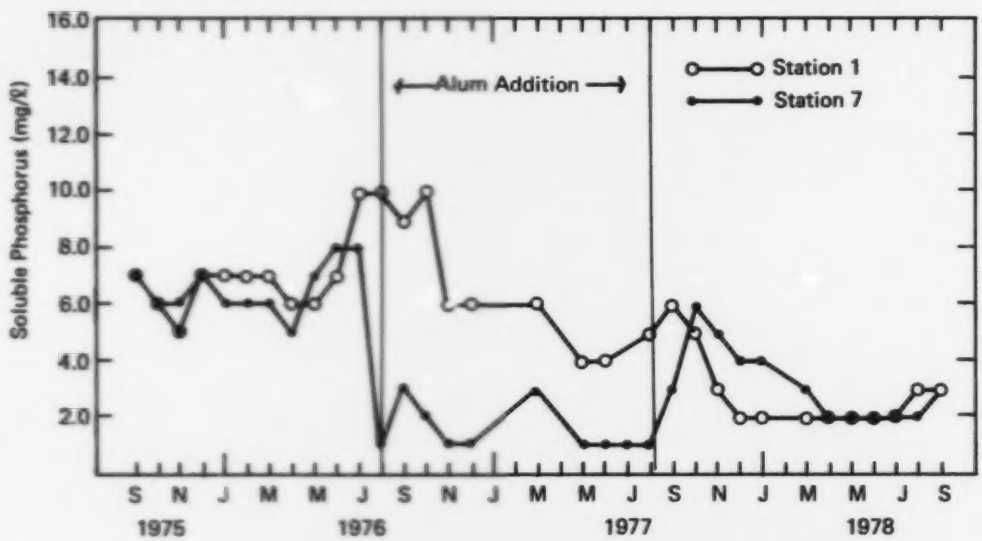

Figure 31. Soluble phosphorus of raw influent and effluent of Cell D.

Total phosphorus concentration in Cell D's effluent decreased 66% from the previous year's concentration. The average total phosphorus concentration in the effluent of Cell D was 2.5 mg/ℓ during alum addition and 7.3 mg/ℓ for the year prior to alum addition. During addition of alum to Cell D, there was an 81% reduction of total phosphorus in the raw influent, compared to a reduction of 24% for the previous year. The soluble phosphorus concentration was reduced 74% from the previous year. During alum addition, the soluble phosphorus concentration averaged 1.6 mg/ℓ compared to a 6.1-mg/ℓ concentration prior to alum addition. The overall phosphorus reduction of the test system was 85% during the period of alum addition to Cell D, compared to 25% the previous year without chemical addition.

The addition of alum to Cell D resulted in a decrease of BOD, suspended solids, total and soluble phosphorous. A significant increase in NH_3N suggests the absence of algae because a substantial amount of ammonia is removed from the water and utilized as a nutrient source in the presence of these organisms. Although the percent reduction in soluble phosphorus improved from 25 to 85%, it was not possible to maintain less than 1-mg/ℓ soluble phosphorus. Total phosphorus could not be maintained at 1 mg/ℓ or less, even though its reduction increased from 24% to 81%.

Alum was fed continuously into Cell D at the transfer pipe from Cell C. Because the lagoon did not discharge continuously, it became apparent that during long periods of no discharge for Cell D, the alum solution seeped through the transfer pipe into Cell C. This was noticed during the last few months of addition to Cell D. A slight head loss from Cell C to Cell D would have prevented this and contained the alum solution in Cell D for more contact with the water in Cell D. When evaluating the chemical addition to a lagoon, the system must be studied so that proper containment of the applied chemical will occur. The defective valve in Cell D caused negative head loss across the cell during periods of no discharge from the test system.

It can be concluded that the BOD standard would be met when alum is added to the third cell of a three-cell system. However, the secondary standard of 30-mg/ℓ suspended solids could not be met consistently.

Third Year Chemical Addition

The yearly and 3-year averages for BOD, COD, TKN, NH_3, NO_2^-/NO_3^-, suspended solids, total and soluable phosphorus are presented in Table 10.

TABLE 10. TEST LAGOON SYSTEM YEARLY AVERAGES*

Year/ Station No	BOD Tot	BOD Sol	COD Tot	COD Sol	TKN	NH_3N	NO_2^-/NO_3^-	Phosphorus Tot	Phosphorus Sol	Suspended Solids
Station 1										
First Year	160	77	307	163	17.8	13.3	0.28	9.6	8.1	134
Second Year	177	89	396	211	27.4	20.7	0.24	13.1	11.0	147
Third Year	118	60	352	159	27.4	26.6	0.27	9.6	7.5	145
Three Yr. Avg.	149	73	349	174	23.4	20.4	0.26	10.6	8.7	141
Station 5										
First Year	31	12	128	58	12.0	10.1	0.27	8.2	7.3	54
Second Year	27	9	137	67	12.5	9.8	0.30	8.3	7.1	51
Third Year	28	8	158	64	16.4	13.6	0.39	3.8	1.9	75
Three Yr. Avg.	29	9	142	62	14.0	11.3	0.30	6.6	5.3	61
Station 6										
First Year	24	10	97	49	9.9	7.5	0.49	7.6	7.1	41
Second Year	24	7	114	56	10.5	8.2	0.24	7.2	6.3	41
Third Year	19	5	111	53	9.3	7.7	0.57	3.6	2.8	45
Three Yr. Avg.	22	7	106	52	9.8	7.8	0.43	6.1	5.3	42
Station 7										
First Year	41	14	152	61	12.5	8.2	0.16	7.3	6.1	72
Second Year	31	12	104	56	15.5	13.9	0.16	2.5	1.6	32
Third Year	26	9	136	68	9.4	8.1	0.75	4.1	3.2	41
Three Yr. Avg.	33	11	178	62	12.1	9.7	0.36	4.8	3.8	53

*Units of all parameters are in mg/ℓ.

BOD and Suspended Solids

During the third year of the study, alum addition was moved to Cell A from Cell D. The method utilized for the addition of alum to Cell A is discussed on page 16. The BOD concentration at Station 5 averaged 28 mg/ℓ during the third year. This represents a 76% reduction in the BOD during this time. The first and second years' BOD removals were 85% and 80% respectively. This indicated a leveling effect, possibly accelerated by the use of alum. The second cell of the test system (Cell C) had a BOD concentration of 19 mg/ℓ in the effluent measured at Station 6, as compared to 24 mg/ℓ for the first and second years, indicating an increase in efficiency during the third year.

Sister Cells B and E of the control system had total BOD concentrations of 28 and 18 mg/ℓ, respectively. There appeared to be no increase in BOD removal in Cells A and C while alum was added to Cell A.

The third and final cell also had a lower BOD effluent concentration during the third year. Possible residual effects of alum addition to Cell D the previous year could have influenced the cell's performance. This cause would have been minor if present at all. In September 1977, when chemical addition terminated to Cell D, the BOD immediately responded with an increase. Any residual chemical effects would have delayed or prevented this increase. The addition of alum to Cell A would require approximately 54 days to begin to effect the performance of

Cell D. After the immediate increase in BOD concentration which occurred when alum addition was terminated to Cell D, the BOD concentration begins to drop and continues to drop until April of 1978. This indicates that the effect of adding alum to Cell A was beginning to appear in Cell D. When the defective valve in Cell D was repaired in May of 1978, the BOD concentration seems to stabilize around 20 mg/ℓ. It can be concluded therefore, that the chemical addition in Cell A had an effect in reducing the BOD concentration of the test system.

During alum addition to Cell A, soluble BOD removal increased in Cells A and C. Efficiency in Cell C increased during the second year, while the efficiency in sister Cell E, decreased. The soluble removal rate during the third year was higher than the baseline year, but not as high as the second year when alum was fed to the final cell. The control system showed no increase in soluble BOD removal during the third year.

The suspended solids concentration in the first cell, Station 5, and second cell, Station 6, increased during the period of alum addition. Cells A and C of the test lagoon system removed 48% and 69% of the applied suspended solids, respectively, compared to 56% and 72% for sister Cells B and E. Final effluent suspended solids concentration for the test system was lower during the chemical addition to Cell A than for the baseline year. The lowest yearly average of suspended solids concentration for the test system occurred during chemical addition to Cell D in the second year. Comparison of the chemical addition in BOD and suspended solids data for the second and third years shows that alum addition to the aerated first cell of a three-cell system is not as efficient in removing BOD and suspended solids as alum addition to the third cell.

The BOD and suspended solids values are presented graphically in Figure 32.

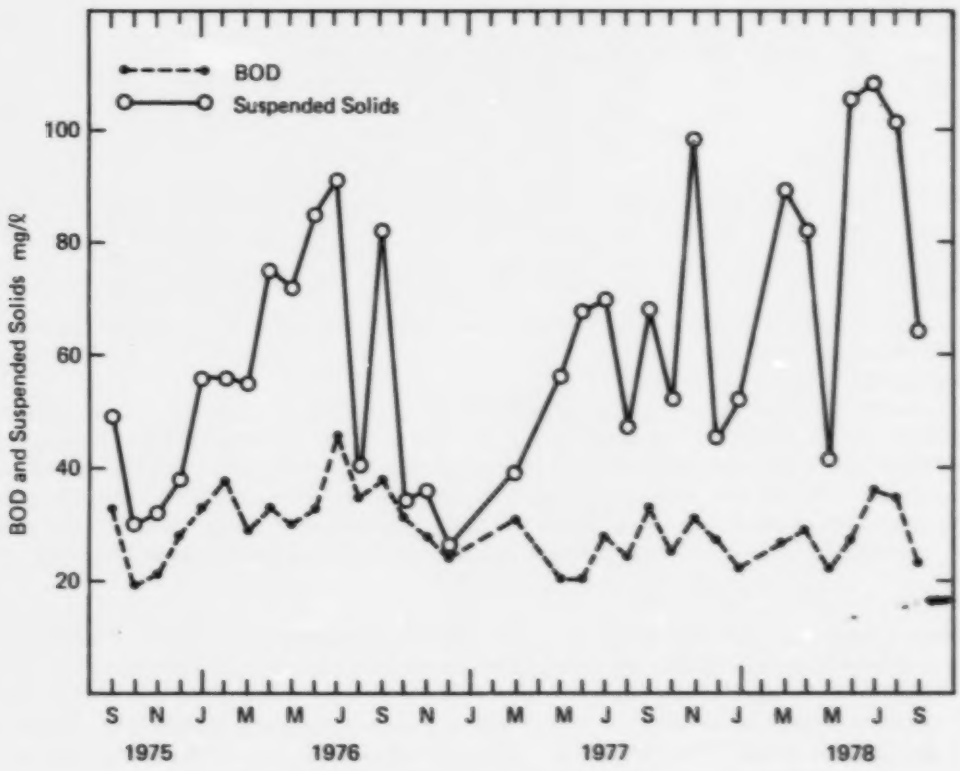

Figure 32. BOD and suspended solids - Cell A (Station 5).

Chemical Oxygen Demand

Cell A had a total COD reduction of 55% during the third year, compared to reductions of 38% and 65% for the first and second years, respectively. The two-cell system of A and C had a lower removal rate the third year in comparison to the two previous years even though Cell C was more efficient the third year than the first and second years. The three-cell system had higher total COD the third and first years, while experiencing a reduction the second year when alum was being applied directly to the final cell. During alum addition to Cell A, the control test system had a significantly higher COD removal rate.

The soluble COD parameter paralleled the characteristics of the total COD concentration. The efficiency of Cell C during the third year was higher than the two previous years.

Chemical addition to the final cell of the three-cell system during the second year, produced a lower soluble COD concentration in the effluent than chemical addition to the first cell of the system during the third year.

Nitrogen

Figure 33 represents the ammonia concentration for the test system at Stations 1 and 5.

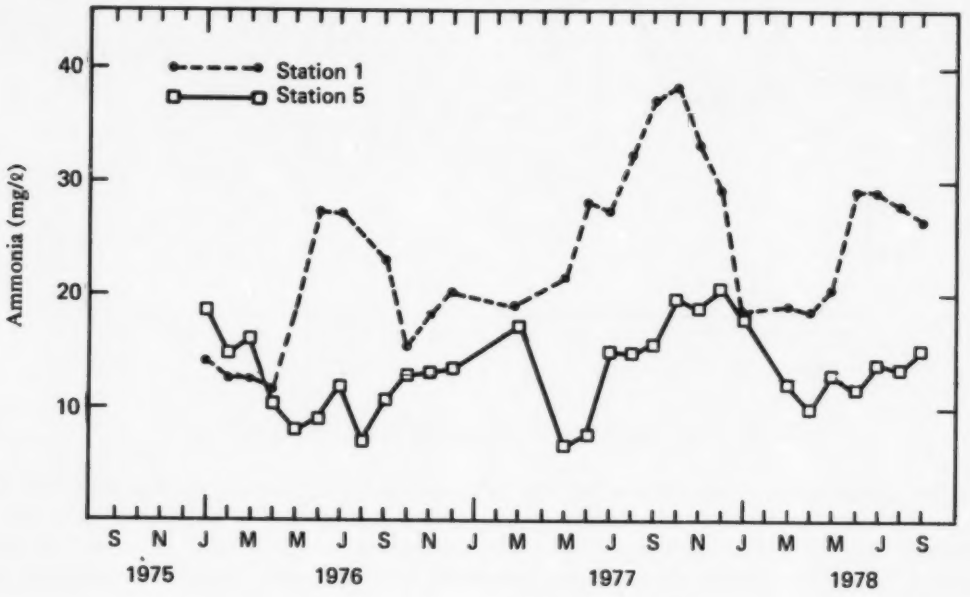

Figure 33. Ammonia of raw influent and effluent of Cell A.

The ammonia concentrations increased in the effluent of Cell A during chemical addition. During the two years prior to alum addition, the average ammonia at Station 5 was 9.8 mg/ℓ. During alum addition, this value increased to 13.6 mg/ℓ. Since ammonia remained constant during the first two years, the increased concentration is attributed to increased organic matter and acidic conditions as were shown in exist in Cell D.

Sulfate

During the year of alum addition to Cell A, sulfates increased 93% in Cell A, to a concentration of 86 mg/ℓ. This increase in sulfate concentration was reduced 22% by Cells C and D to a final effluent concentration of 67 mg/ℓ. The baseline effluent concentration was 35 mg/ℓ. During the second year, while alum addition to Cell D was being conducted, the final effluent concentration was 142 mg/ℓ. This increase in sulfate levels in the final effluent during the second and third years is to be expected with the addition of alum.

During the year of alum addition to Cell A, the sulfate characteristics of the control system did not change significantly. The control lagoon system experienced a 17% reduction in the sulfate concentration during the third year with a final effluent concentration of 37 mg/ℓ. The effects of the increased sulfate concentration in the effluent applied to land for final disposal was not examined in this study.

Total Phosphorus

Figure 34 represents the total phosphorus concentration for Cell A of the test system.

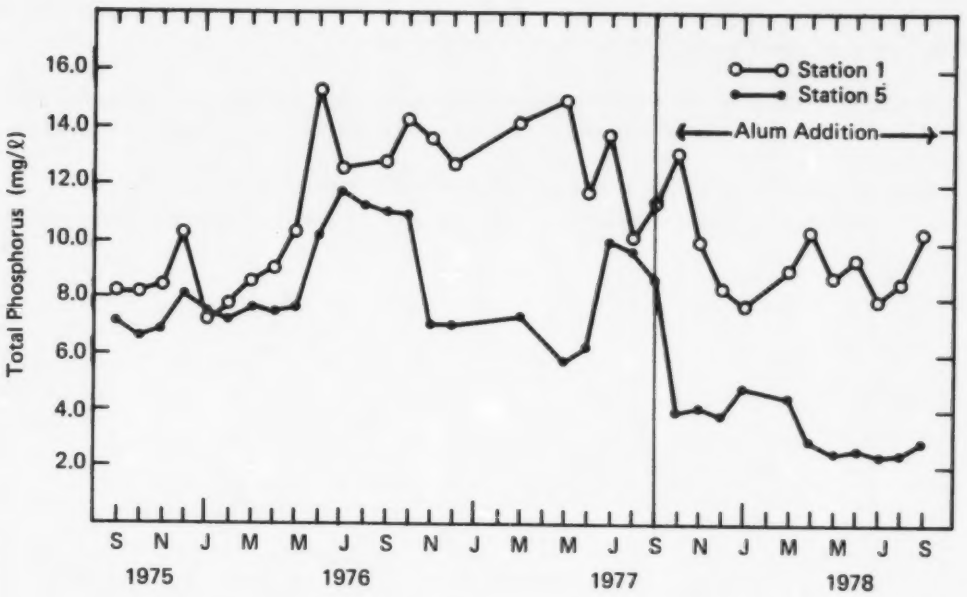

Figure 34. Total phosphorus of raw influent and effluent of Cell A.

The total phosphorus concentration in Cell A effluent was 3.8 mg/ℓ during the third year. This compares to 8.2 and 8.3 mg/ℓ for the first and second years, respectively. During the first and second years, Cell A had a 27% reduction in total phosphorus, while it had a 60% removal rate during chemical addition in the third year. Cell C had a 5% reduction during the third year, contrasting a 10% reduction during the first and second years.

Phosphorus removal increased in the first cell but not in the two following cells. Little additional phosphorus removal occurs in Cell C and the concentration actually increases in Cell D. During the third year, the effluent of Cell D had a 14% increase in phosphorus over its influent, even though the baseline year showed a natural 4% decrease occurring in Cell D.

The data for the baseline year shows that the three-cell test lagoon system had averaged a 25% reduction in total phosphorus concentration. The data from the second year in which chemical addition to Cell D occurred, shows that the three-cell system had averaged an 81% reduction in phosphorus. Alum addition to Cell A during the third year caused a 60% reduction in phosphorus. The control lagoon system had a 25%, 37%, and 50% reduction in phosphorus for the first, second, and third years respectively. The effluent concentration at Station 7 during the third year was 4.1 mg/ℓ, compared to 4.8-mg/ℓ phosphorus concentration in the control system effluent and 2.5-mg/ℓ phosphorus in the test system when alum was added to Cell D during the second year.

The Al/P ratios and dosage rates for Cell A are shown in Table 11.

TABLE 11. Al/P RATIOS AND DOSAGE RATES FOR CELL A

Date	Avg. Flow MGD	Feed Rate mℓ/min	Al Dosage Rate mg/ℓ	P Reduction %	Al/P
9/77	0.193	160	18.5	20	1.9/1
10/77	0.092	160	38.8	56	3.4/1
11/77	0.211	160	17.0	59	1.9/1
12/77	0.244	160	14.6	54	2.0/1
1/78	0.223	160	16.0	35	2.4/1
2/78	0.481	88	4.3	42	0.5/1
3/78 (a)	0.534	88	3.7	30	0.4/1
3/78 (b)	0.534	164	6.8	50	0.8/1
4/78	0.273	164	13.4	72	1.5/1
5/78	0.488	164	7.5	71	1.1/1
6/78	0.470	164	7.8	70	1.0/1
7/78	0.371	164	9.9	70	1.4/1
8/78	0.473	164	7.7	72	1.0/1
9/78	0.402	164	9.1	72	1.0/1

Figure 35 compares the total phosphorus concentration in the effluent of Cell A and the calculated Al to P ratio (Al/P) over a one-year period.

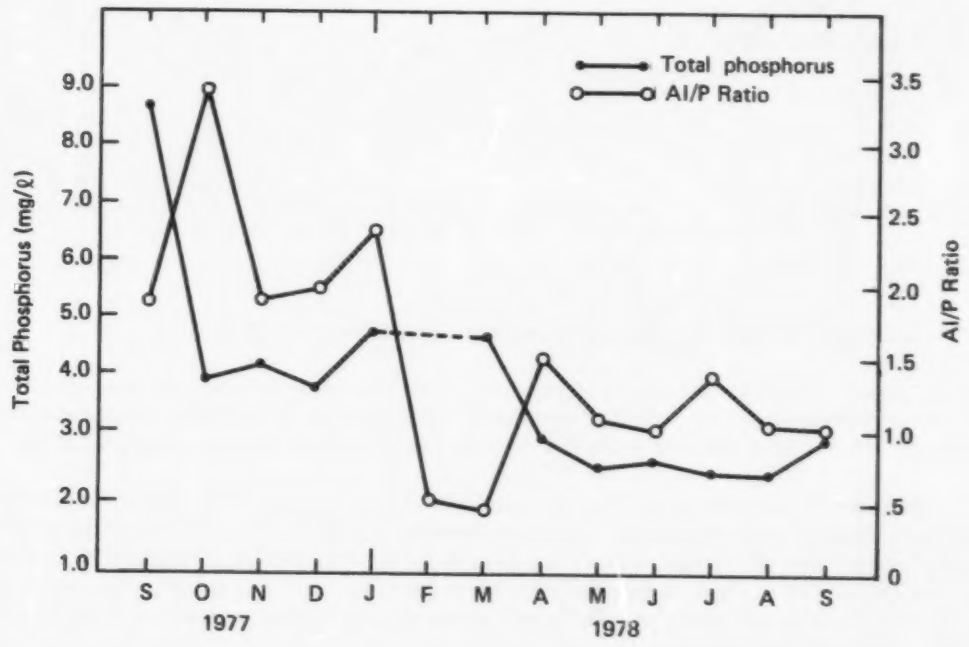

Figure 35. Total phosphorus vs Al/P ratio in Cell A.

This figure shows that from September 1977 to January 1978, the average Al/P was 2.3 to 1, with an average effluent phosphorus concentration of 5.1-mg/ℓ. During April 1978 to September 1978, the Al/P was 1.1 to 1, with an effluent phosphorus concentration of 2.6 mg/ℓ. During February and March of 1978, the chemical feed rate was reduced to provide an Al to P ratio of approximately 0.5 to 1 which caused the phosphorus concentration in the effluent to increase. At no time was a 1-mg/ℓ total phosphorus concentration achieved during the third year, either in the final effluent or in the effluent of Cell A. The lowest phosphorus concentration reached was 2.5 mg/ℓ in the effluent of Cell A and 2.3 mg/ℓ in the three-cell test system.

Soluble Phosphorus

Figure 36 represents the soluble phosphorus concentration for Cell A of the test system.

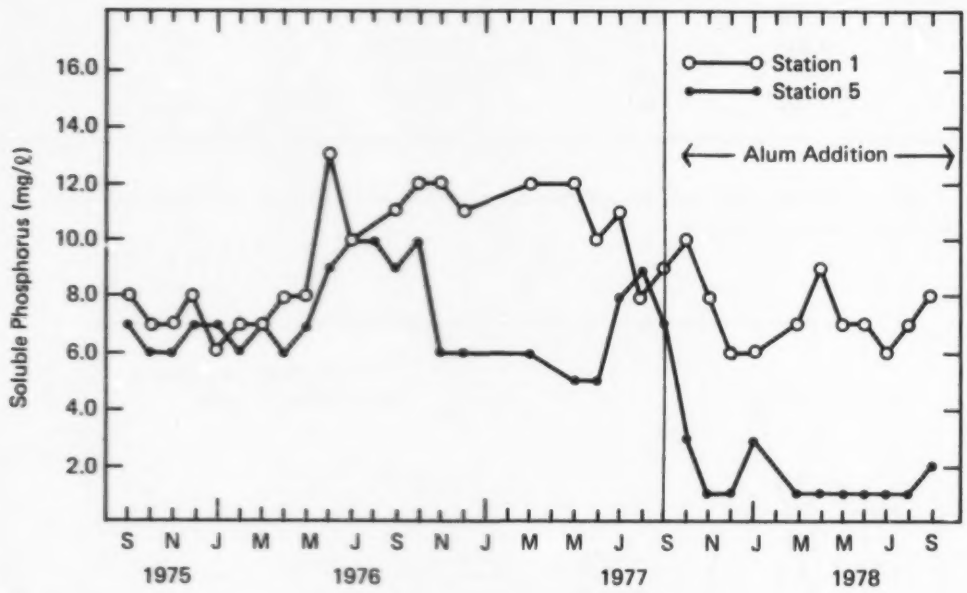

Figure 36. Soluble phosphorus of raw influent and effluent of Cell A.

The soluble phosphorus concentration in Cell A was reduced 10% of the first year (baseline) concentration; 35% the second year and 75% the third year when alum was added to the influent of Cell A. This compares to a reduction of 12%, 26%, and 29% for Cell B, the sister cell of Cell A, during the first, second and third years respectively.

During chemical addition to Cell D in the second year, Cell D experienced the same 75% reduction in soluble phosphorus concentration that occurred when alum was added to Cell A. However, chemical addition to Cell A produced a concentration of 3.2-mg/ℓ soluble phosphorus in the final effluent and chemical addition to Cell D produced a concentration of 1.6 mg/ℓ in the effluent. It can therefore be concluded that alum addition to Cell A did cause a reduction in total and soluble phosphorus concentrations in the final effluent but not as significant a reduction as the addition of alum to Cell D.

Nitrification Study

The third task of the project was to evaluate a plastic media trickling filter nitrification tower on the basis of efficiency and process dependability. The data pertaining to tower operation are presented in Appendices A and B. The monthly averages for the parameters at Stations 7 and 8 are presented in Table 12.

TABLE 12. TOWER INFLUENT AND EFFLUENT DATA

	Station 7							Station 8							
Year/Month	pH	Temp °C	TKN mg/ℓ	NH_3 mg/ℓ	NO_2^-/NO_3^- mg/ℓ	D.O. mg/ℓ	Alk mg/ℓ	pH	Temp °C	TKN mg/ℓ	NH_3 mg/ℓ	NO_2^-/NO_3 mg/ℓ	D.O. mg/ℓ	Alk mg/ℓ	%NH_3 Conv.
1977															
September	6.7	18.9	9.1	6.7	0.12	2.5	120	7.4	20.5	9.7	7.2	0.91	7.3	141	3
October	6.9	10.8	10.6	8.7	0.18	1.5	152	6.9	12.9	8.0	5.7	4.06	7.4	128	34
November	6.7	11.3	13.6	11.8	0.14	1.9	139	6.4	12.6	8.3	6.5	5.60	8.8	106	45
December	6.3	3.9	16.1	14.6	0.14	0.4	136	6.0	5.1	12.5	10.4	3.52	10.4	113	29
1978															
January	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
February	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
March	7.2	7.0	12.6	11.4	0.14	3.5	127	7.3	8.0	13.3	11.8	0.72	9.5	125	4*
April	7.2	12.0	11.4	9.8	0.17	6.9	120	7.2	12.6	6.8	5.2	4.62	8.5	109	47
May	7.4	16.2	6.4	5.3	0.41	14.8	98	7.2	18.7	2.4	1.1	4.64	8.6	56	79
June	7.4	24.7	4.1	2.9	0.83	14.9	108	7.3	24.7	1.5	0.4	3.88	9.9	87	86
July	7.0	26.5	4.2	3.1	1.07	13.1	98	7.0	27.1	1.5	0.5	4.63	9.8	77	84
August	7.7	27.2	4.2	3.1	2.45	11.6	89	8.1	27.7	1.2	0.4	6.11	8.8	70	88
September	7.7	21.3	5.1	4.0	3.09	10.1	95	7.9	23.0	1.9	0.9	6.57	9.3	75	78
Average		16.2	8.9	7.5	0.79	7.4	116		17.5	6.1	4.6	4.28	8.9	99	39

* % Increase

— Tower shutdown due to cold weather

Data collection on the nitrification tower was initiated on September 26, 1977 when the tower was started after a 30-day shut down period. A 5-day period was required to establish nitrifying activity with the existing influent characteristics. Initiation of nitrification was indicated through chemical analysis and by extensive foaming in the cone at the tower bottom and tower discharge.

Conditions during the first 6 months of nitrification studies were represented by low temperatures and decreasing biological activity, with a corresponding rise in ammonia. Other factors such as D.O. and pH were also below optimal levels based on previous studies (25). The pH ranged from 6.3-6.9, while D.O. ranged from 0.4-2.5 mg/ℓ. These factors as mentioned previously, are critical to the nitrification process and may have influenced nitrification and NH_3 reduction efficiencies during the period September 1977-December 1977.

Maximum efficiencies for the September 1977-December 1977 period were attained in November (see Table 12), during which time the NH_3 conversion was 45%. Data recorded for September 1977 showed a net increase in NH_3 across the tower due to sloughing off of dead organic material from the tower media. This is also indicated by the net increase in suspended solids and BOD as shown in Table 13.

TABLE 13. TOWER INFLUENT AND EFFLUENT RELATIONSHIPS FOR BOD AND SUSPENDED SOLIDS

Year/ Month	Station 7 Total BOD (mg/ℓ)	Station 7 Total Suspended Solids (mg/ℓ)	Station 8 Total BOD (mg/ℓ)	Station 8 Total Suspended Solids (mg/ℓ)
1977				
September	29	92	36	142
October	40	69	38	82
November	35	72	37	55
December	41	46	33	30
1978				
January	—	—	—	—
February	—	—	—	—
March	22	50	23	45
April	20	57	17	48
May	22	74	22	58
June	17	41	19	54
July	26	55	20	46
August	18	28	18	29
September	19	35	15	27
Average	26	56	25	56

— Data not available.

September 1977	Averages for stations includes last two days of month
November 1977	Includes suspended solids data for 10 and 11
March 1978	Includes all suspended solids data for Stations 7 and 8
April 1978	Includes all BOD data for Stations 7 and 8
January 1978	All Station 7 data omitted

During January 1978, severe freezing temperatures necessitated the shut down of the tower. On February 24, 1978, startup was initiated; however, due to much colder temperatures, 34 days were required to achieve nitrification activity. Nitrogen increases across the tower recorded in March 1978 indicated that dead organic material was being sloughed off the media following tower restart in February 1978. This is shown by the net increase in BOD in Table 13.

Consistent nitrification was achieved from May 1978 through September 1978, averaging 83%. Table 14 shows no significant difference between the tower influent and effluent organic nitrogen during the 12-month study.

TABLE 14. TOWER INFLUENT AND EFFLUENT RELATIONSHIPS FOR ORGANIC NITROGEN

Year/Month	Station 7 Org N (mg/ℓ)	Station 8 Org N (mg/ℓ)
1977		
September	1.7	2.5
October	1.9	2.3
November	1.8	1.8
December	1.5	2.1
1978		
January	—	—
February	—	—
March	1.2	1.5
April	1.6	1.6
May	1.1	1.3
June	1.2	1.1
July	1.1	1.0
August	1.0	0.8
September	1.1	1.0
Average	1.4	1.5

— Data not available.

Nitrification activity for the month of April 1978 is representative of a period during which increased nitrifier activity was occurring. This is indicated in Table 12 by nitrification values intermediate to those recorded during March and May 1978. During the March-May period, tower influent pH, D.O. and temperature increased to values which are more optimal to the nitrification process (25). These parameters changed as a result of moderating environmental conditions and elimination of an influent leak in Cell D. The combined effect of the changes in influent quality and ambient temperatures is reflected by increases in nitrification efficiency from 4% in March 1978, to 79% in May 1978. Irrespective of the reason for the changes in tower influent, the results show that influent chemical quality and ambient temperature effect tower operation efficiency.

Influent consisted of high BOD, low pH and low temperatures when low levels of nitrification were observed from September to December 1977. Consistent high rate nitrification (>80% NH_3 conversion) was maintained during the warmer months (May 1978 - September 1978). In view of the results obtained during the 12-month sampling period, process dependability for nitrification seems to be strongly related to favorable environmental conditions.

Nitrification studies conducted in the past have shown the nitrifying process to be relatively low in solids yield (25). The data collected in this study would seem to substantiate these previous findings. Although the final effluent exceeded the secondary standard of 30-mg/ℓ suspended solids, this can be attributed to higher influent suspended solids concentrations. Average results for the 12-month sampling period show no significant difference between influent and effluent suspended solids, except for periods following initial startup and sloughing.

BOD data listed in Table 13 and Figure 37 show no significant difference between tower influent and effluent.

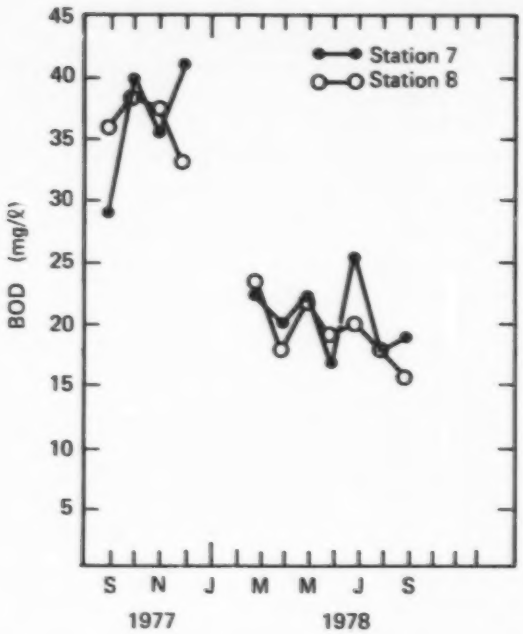

Figure 37. BOD tower influent and effluent.

As stated earlier, hydrogen ions produced during the nitrification process destroy alkalinity at a ratio of 7.14 mg $CaCO_3$/1.0 mg NH_3 oxidized to NO_2^- (37). From data listed in Table 12 for months during which nitrification occurred, an average ratio of 6.9 mg $CaCO_3$/1.0 mg NH_3 was obtained. This is in general agreement with the above theoretical value.

Microbiological Correlation

Total algae counts for the test and control systems are provided in Table 15 and depicted in Figures 38 and 39 respectively. Figures 38 and 39 indicate that both systems follow similar annual patterns with respect to total phytoplankton concentrations. The control system shows a gradual increase in algal density from October 1977 through March 1978 (Figure 39). A similar trend is shown in Figure 38; however, the algae population appears to be less stable than that of the control system. Both the test and control systems show a sharp decline in the algae population during May 1978. This decline was most probably due to grazing activities of zooplankton such as Rotifers and *Daphnia* which were present in large numbers during May. Following the low densities in May, algae populations in both systems showed a rapid recovery reaching a peak in July 1978. This is followed by a gradual decrease in both systems, most probably the result of declining water temperatures.

TABLE 15. TOTAL ALGAE-COUNTS X 10^3/mℓ

	Control System			Test System		
	Cell B	Cell E	Cell F	Cell A	Cell C	Cell D
1977						
October	18	12	6.4	13	24	42
November	39	38	34	22	43	111
December	38	57	90	5.2	75	4.3
1978						
January	18	37	72	8.9	14	6.8
February	33	81	119	46	127	133
March	65	75	149	95	46	44
April	43	30	27	117	40	66
May	10	4.5	3.8	8.4	8.8	14
June	31	42	32	16	20	47
July	33	161	265	39	272	349
August	25	65	61	21	61	198
September	19	55	16	23	31	72
Average	31	55	73	35	63	91

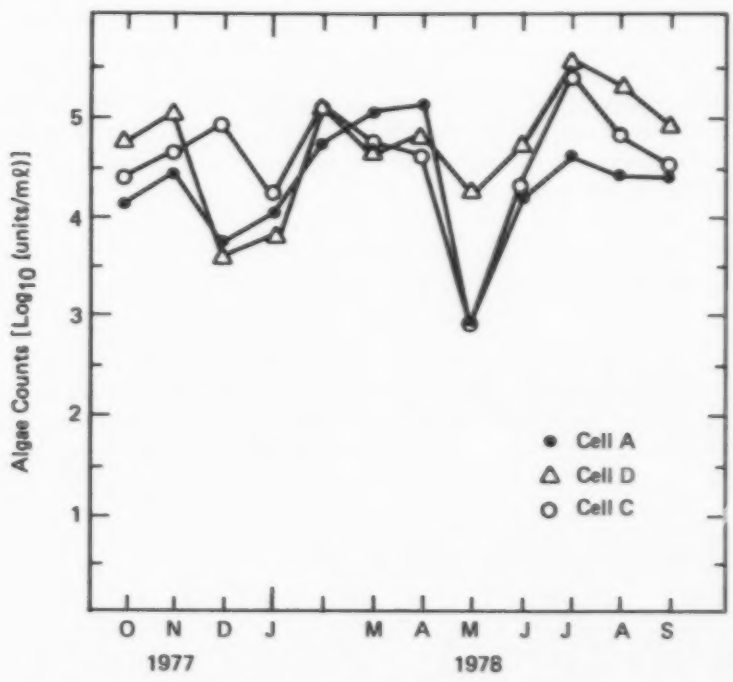

Figure 38. Total algae counts for the test system.

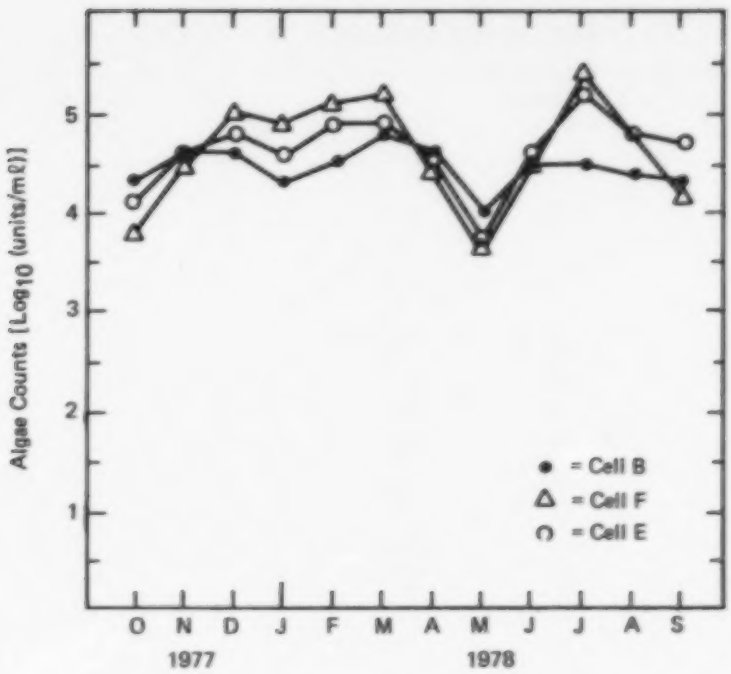

Figure 39. Total algae counts for the control system.

Euglenophyta

The Division Euglenophyta was represented by two species of *Euglena*. Examination of Figures 40 and 41 show a regular decline in the density of *Euglena*, beginning in November and ending in February 1978, with complete disappearance in both systems. This suggests that in addition to other parameters, water temperature is a primary factor in controlling the density of *Euglena*.

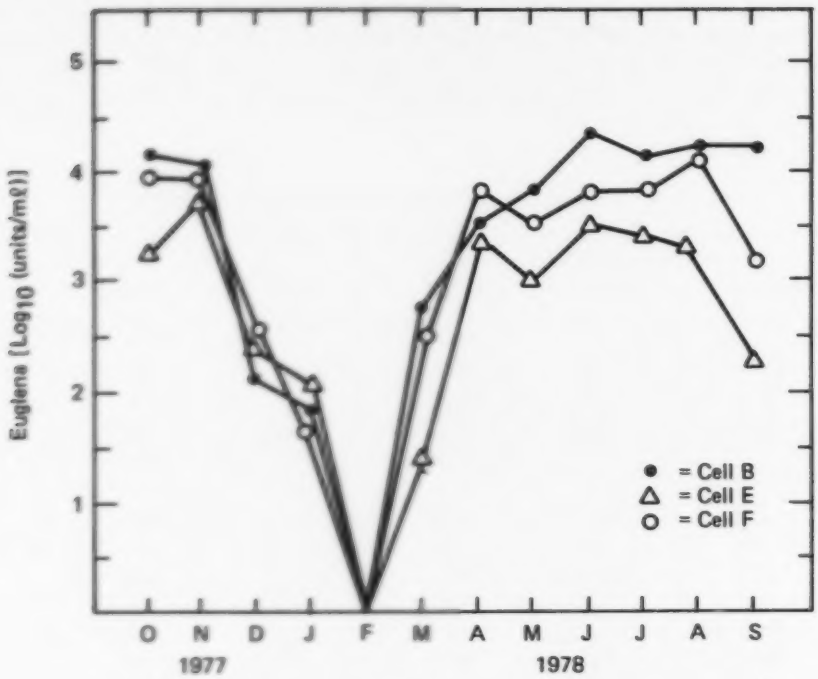

Figure 40. Density of *Euglena* in the control system.

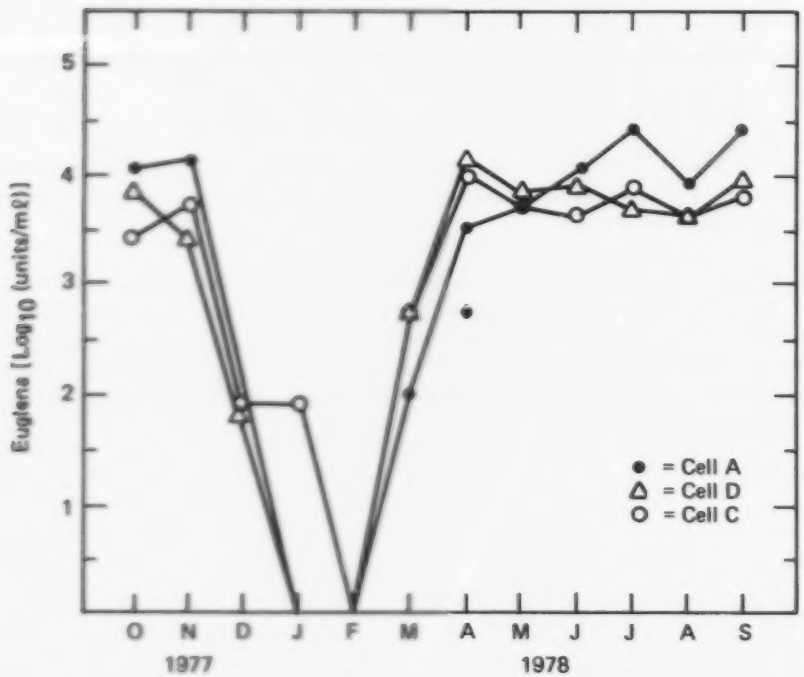

Figure 41. Density of *Euglena* in the test system.

While it is not readily apparent in Figures 40 and 41, examination of Table 16 indicated the population of *Euglena* to be more dense in the influent (Cells A and B), with a gradual decrease in the following cells in the control system. Apparently *Euglena* is more competitive in the influent cells due to a higher tolerance to the more polluted water. The population density in Cell D however, shows an increase over that of Cell C in the test system.

TABLE 16. EUGLENA COUNTS X 10^3/mℓ

Year/ Month	Control System Cell B	Cell E	Cell F	Test System Cell A	Cell C	Cell D
1977						
October	13	8.6	1.7	9.0	2.5	4.7
November	9.3	8.7	5.2	11	3.9	2.6
December	0.11	0.34	0.27	0.18	0.07	0.06
1978						
January	0.06	0.04	0.11	- 0 -	0.07	- 0 -
February	- 0 -	- 0 -	- 0 -	- 0 -	- 0 -	- 0 -
March	0.54	0.32	0.03	0.09	0.52	0.50
April	3.2	6.9	2.5	2.8	9.7	11
May	67	3.1	0.94	4.7	5.4	5.6
June	18	6.8	2.8	9.5	3.9	6.1
July	13	6.3	2.4	28	5.8	5.2
August	16	11	2.2	8.4	4.0	3.9
September	15	1.5	0.21	14	5.6	7.9
Average	8.1	4.5	1.5	7.4	3.4	4.0

Chlorophyta (Green motile algae)

Green motile algae in the Division Chlorophyta were represented by *Pandorina, Eudorina* and three species of *Chlamydomonas. Volvox* was observed occasionally during preliminary examinations; however, it was never observed during enumeration procedures.

Figures 42 and 43 graphically depict the population dynamics of the green motile forms identified in the lagoon system. These algae were always present in both systems, except during December 1977 when none were observed in Cell A of the test system. *Eudorina* and *Pandorina* were the less abundant forms appearing only sporadically throughout the 12-month sampling period. The three species of *Chlamydomonas* (designated in this study as *Chlamydomonas* $_1C_2$ and C_3) by far were the more abundant forms, and have had the greatest impact on the slopes of the curves in Figures 42 and 43.

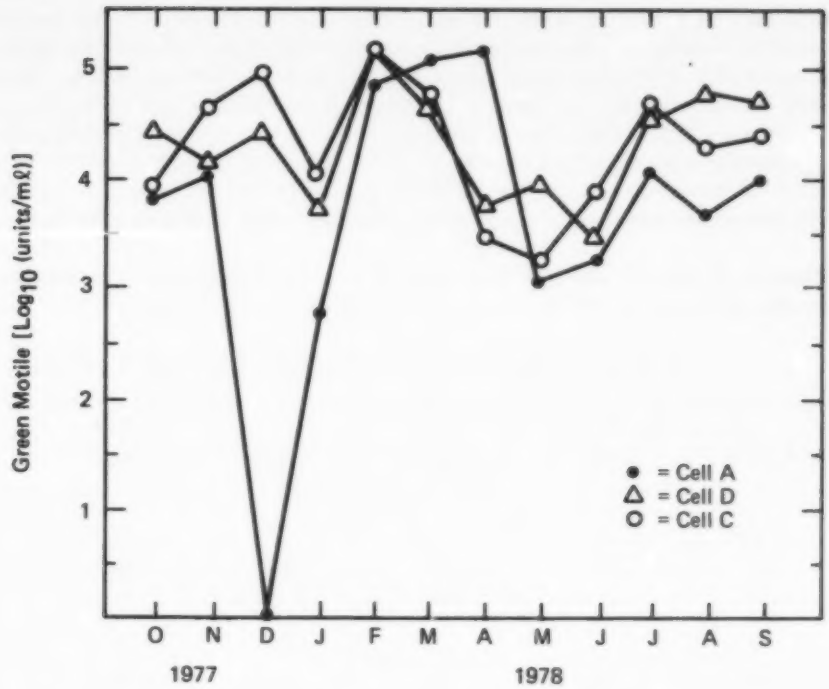

Figure 42. Population dynamics of green motile forms in the test system.

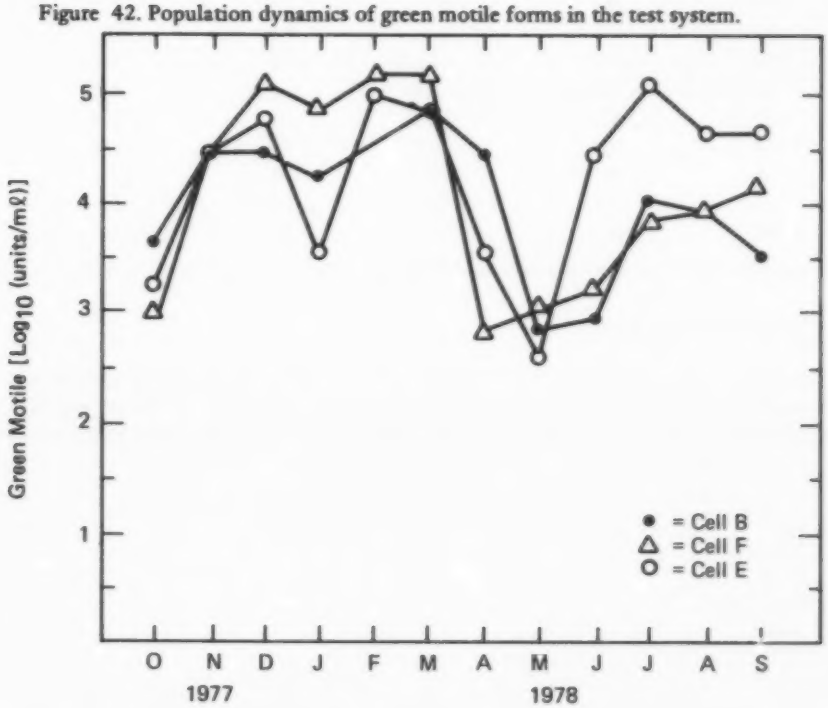

Figure 43. Population dynamics of green motile forms in the control system.

Except for the December 1977 period in Cell A and the May 1978 period in both systems, the gradual increase and decrease in the population density represents ecological replacement of one species of *Chlamydomonas* by another. During October 1977, *Chlamydomonas*$_1$ was the more abundant species, but was gradually replaced by *Chlamydomonas*$_2$ in November 1977. *Chlamydomonas*$_2$ was clearly the dominant species in December, with *Chlamydomonas*$_1$ being observed in only one sample. From January 1978 through the middle of May 1978, *Chlamydomonas*$_3$ gradually increased in density over *Chlamydomonas*$_2$ to be more abundant than *Chlamydomonas*$_3$ and also during this period, *Chlamydomonas*$_1$ reappeared in both systems. From June 1978 through August 1978, *Chlamydomonas*$_3$ disappeared and *Chlamydomonas*$_2$ remained dominant over *Chlamydomonas*$_1$. The period August 1978 through September 1978 showed *Chlamydomonas*$_1$ to increase in density over that of *Chlamydomonas*$_2$.

Examination of Table 17 indicated the concentration of *Chlamydomonas* to be less dense in the influent cells and the density in the last two cells in each series not being significantly different.

TABLE 17. MOTILE GREEN ALGAE COUNTS X 10^3/ml

Year/ Month	Control System			Test System		
	Cell B	Cell E	Cell F	Cell A	Cell C	Cell D
1977						
October	4.0	1.7	1.0	7.0	7.7	25
November	27	27	27	10	36	12
December	26	54	89	-0-	71	22
1978						
January	15	3.2	65	0.52	10	5.1
February	33	80	117	46	127	132
March	64	67	123	92	45	43
April	27	2.9	0.60	112	2.3	4.6
May	0.57	0.38	1.0	1.0	1.4	7.9
June	0.72	23	1.5	1.5	6.3	2.6
July	11	95	6.0	11	40	30
August	7.2	42	8.5	3.7	16	48
September	2.8	42	11	7.5	22	38
Average	18	36	37	24	32	31

Chlorophyta (Green nonmotile algae)

The nonmotile green algae represented the most diverse group encountered with respect to total numbers of genera identified. Table 18 lists the different genera observed during the 12-month sampling period. These include all genera classified in the Division Chlorophyta, except the motile forms placed in the Order Volvocales.

TABLE 18. PHYTOPLANKTON GENERA IDENTIFIED

Division	Genus
Euglenophyta*	*Euglena*
Chlorophyta	*Chlamydomonas*
	Pandorina
	Tetraedron
	Ankisstrodesmus
	Actinastrum
	Closteridium
	Trocbiscia
	Phytoconis
	Chlorella
	Oocystis
	Colenkina
	Scenedesmus
	Chloroscarcina
	Closterium
Cyanophyta	*Artbrospira*
	Oscillatoria
	Spirulina
	Trichodesmium
	Agmenellum
	Anabaena
	Raphidiopsis
	Unidentified

* Classification according to Prescott (24)

Figures 44 and 45 show the population densities of this group for the test and control systems respectively. It is evident that the influent cells of both systems maintain a less stable population of nonmotile green algae when compared to the last two cells in series. This is indicated by "0" population densities during October 1977, and February and August 1978 for the test system and February 1978 for the control system.

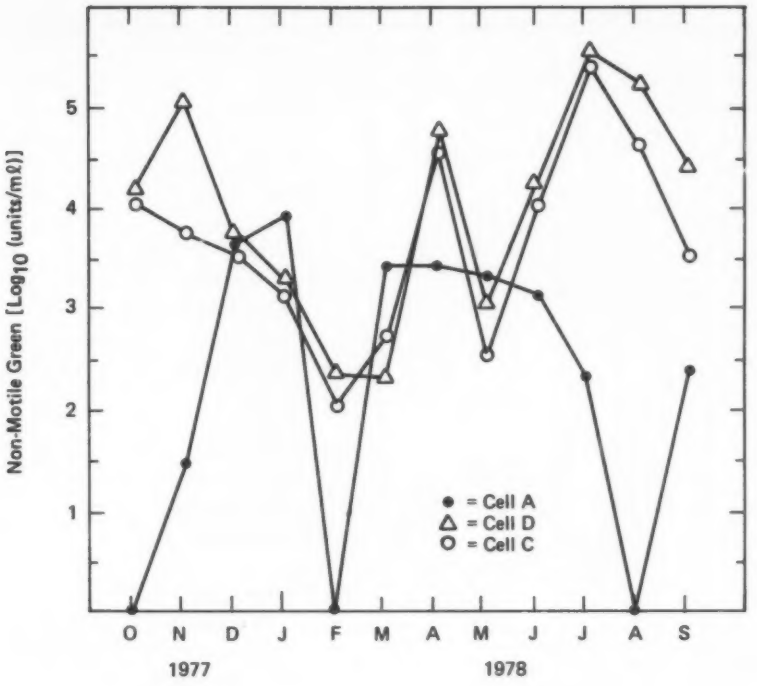

Figure 44. Population densities of nonmotile green algae for the test system.

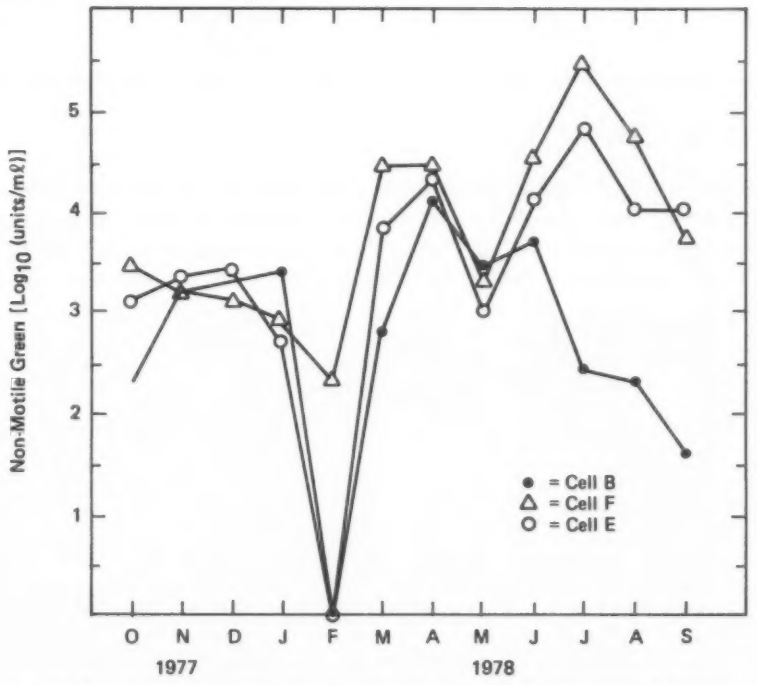

Figure 45. Population densities of nonmotile green algae for the control system.

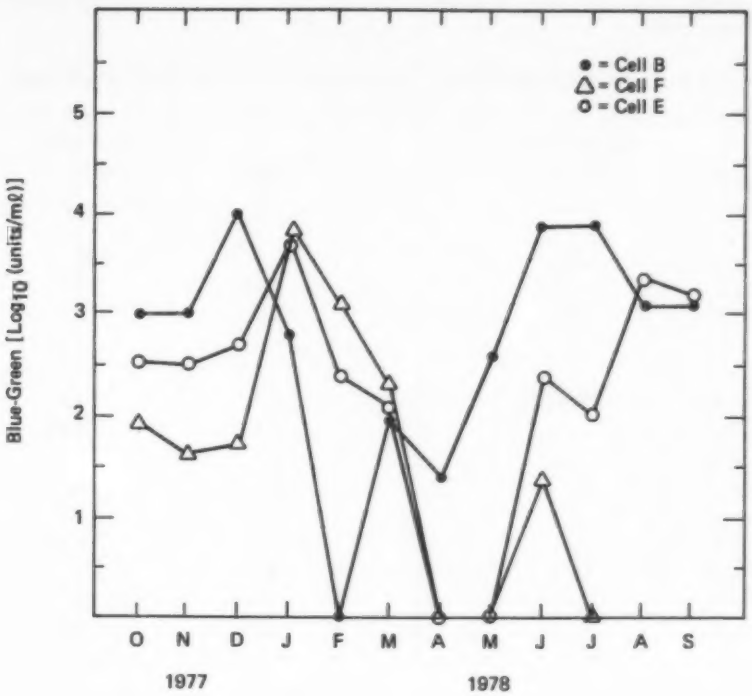

Figure 46. Densities of blue-green algae in the control system.

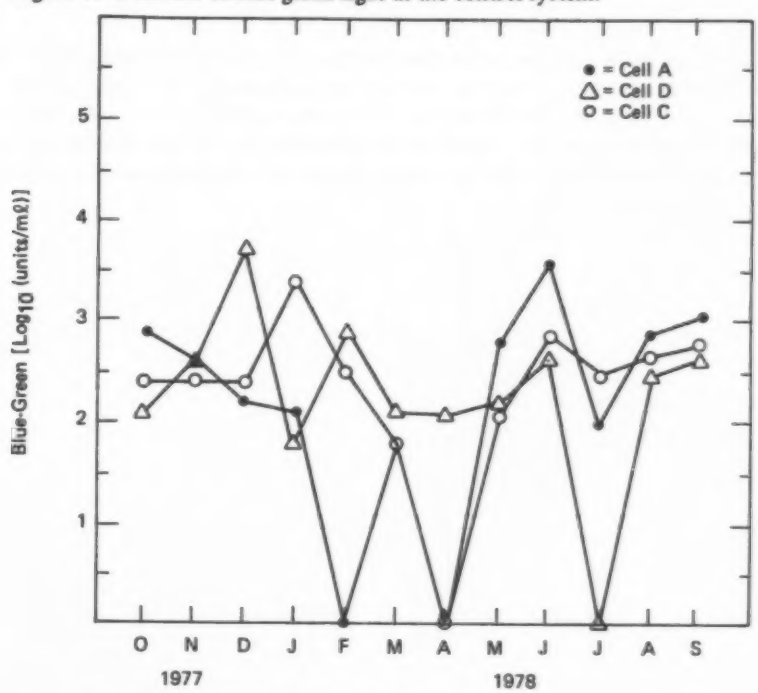

Figure 47. Densities of blue-green algae in the test system.

Table 19 clearly shows that this group is more abundant for both systems in the last two cells in each series than in the two influent cells.

TABLE 19. NONMOTILE GREEN ALGAE COUNTS X 10^3/mℓ

Year/ Month	Control System Cell B	Cell E	Cell F	Test System Cell A	Cell C	Cell D
1977						
October	0.20	1.3	2.7	- 0 -	102	12
November	1.6	1.7	1.7	0.02	5.1	95
December	1.9	2.5	1.3	3.8	3.2	3.1
1978						
January	2.5	0.46	0.85	8.3	1.3	1.6
February	- 0 -	- 0 -	0.19	- 0 -	0.09	0.19
March	0.57	6.8	25	2.7	0.44	0.18
April	12	20	24	2.5	28	50
May	2.3	1.0	1.8	2.0	0.33	0.89
June	5.3	12	28	1.1	9.0	14
July	0.22	59	255	0.18	225	313
August	0.18	9.3	50	- 0 -	40	146
September	0.04	9.7	5.2	0.02	3.2	26
Average	2.2	10	33	1.7	27	55

Cyanophyta

The blue-green algae were the least abundant forms observed in the lagoon system. Seven different genera were identified as indicated in Table 18 under the Division Cyanophyta. *Rapbidiopsis* was the most abundant form present and occurred regularly throughout the 12-month sampling period. All other blue-greens appeared sporadically. Figures 46 and 47 show the population densitites for the test and control systems, respectively. The wide fluctuations in densities in both systems are a result of short and temporary increases in a given genus.

Table 20 shows that blue-greens tend to be more dense in the influent cells of both systems and decrease in density with the following cells in each series.

TABLE 20. BLUE-GREEN ALGAE COUNTS X 10^3/mℓ

Year/ Month	Control System			Test System		
	Cell B	Cell E	Cell F	Cell A	Cell C	Cell D
1977						
October	0.93	0.32	0.08	0.71	0.27	0.11
November	1.0	0.32	0.03	0.39	0.23	0.38
December	9.5	0.48	0.04	0.14	0.25	4.7
1978						
January	0.67	4.5	6.2	0.11	2.3	0.05
February	- 0 -	0.23	1.3	- 0 -	0.28	0.86
March	0.09	0.12	0.19	0.06	0.06	0.12
April	0.02	- 0 -	- 0 -	- 0 -	- 0 -	0.12
May	0.41	- 0 -	- 0 -	0.65	0.11	0.14
June	7.8	0.24	0.02	4.1	0.87	0.53
July	8.2	0.10	- 0 -	0.10	0.34	- 0 -
August	1.3	2.3	- 0 -	0.75	0.52	0.35
September	1.3	1.5	- 0 -	1.3	0.59	0.45
Average	2.6	0.85	0.66	0.70	0.49	0.65

The algae genera identified in the St. Charles lagoon system are typical of those inhabiting a polluted environment (26). Relative densities follow an annual cyclic pattern as a result of environmental and biological influences, with maximum peak densities occurring in July. The diverse planktonic populations characteristic of the final cells in series indicate that the lagoon system is operating below maximum loading. However, it is hypothesized that the high densities during the warmer months contribute significantly to the organic suspended matter in the final effluent.

Economic Considerations

The cost for nutrient removal is normally expressed as cost per 1,000 gal. Alum addition to Cell D produced an effluent with an average total phosphorus concentration of 2.5 mg/ℓ, while alum addition to Cell A produced an effluent with 4.1 mg/ℓ average total phosphorus concentration. This represents removal rates of 81% and 60%, respectively.

The costs to maintain these rates, using liquid alum, is estimated to be 9.6 cents/1,000 gal for addition to the third cell and 6.1 cents/1,000 gal for addition to the first cell. The higher removal rates which occurred in Cell D produced an average cost of $2.60/ lb P removed. This compares to an average cost of $3.04/lb P removed during alum addition to Cell A. Based on present costs, percent removal rates, and the natural reduction of phosphorus in the first cell, it would be more economical to utilize in-cell alum addition to the third cell in order to obtain a desired 1.0 mg/ℓ total phosphorus concentration in the effluent.

Nitrification of the effluent of Cell D produced a consistent ammonia reduction of 83% after the tower had equilibrated. Since the facility that was studied used a side stream to test, the projected operating costs were not determined. These costs would include rental fees, as compared to a facility using a tower to nitrify the entire effluent, in which case the purchase price would be needed. The values may also vary depending on the size of the lagoon and the type of operation employed.

Since the tower operation is dependent on the climatic conditions at the installation site, consideration should be given to site specific environmental conditions, such as temperature, when considering the operating and maintenance costs.

SECTION 7

SUMMARY

The major benefit of this project has been the generation of reliable and sufficient data to assess accurately the feasibility and project the cost of (a) removing phosphorus from lagoon effluents utilizing in-cell alum addition, and (b) nitrifying lagoon effluent by passage through a plastic-media, attached-growth biological system. These methods of controlling phosphorus and nitrogen compounds in lagoon effluents were selected for long-term evaluation from a vast number of possible processes that involve more complex unit operations producing a larger volume of solids to be treated.

It was found that both in-cell alum addition and tertiary plastic-media nitrification are compatible with lagoon operation and will not destroy the basic simplicity and relative ease of operation that has made lagoons attractive to small communities. The results should be of interest to design engineers and regulatory personnel holding the responsibility for approving permits for lagoon effluent discharges.

It is hoped that these data, as well as the conclusions and recommendations from this project, will have a significant impact on new and upgraded lagoon designs that not only must incorporate nutrient control, but also effect improved overall treatment.

REFERENCES

1. Federal Water Pollution Control Act, As Amended (33 U. S. C. 466 et seq.), 1977.

2. Maryland Water Resources Administration Newsletter, WRA Reports, "Suspended Solids Limits for Municipal Discharge Permits," Fall 1978.

3. Porges, R., and K. M. Mackenthun, Waste Stabilization Ponds: Use, Function, and Bioata, Biotechnology and Bioengineering, 5(4):255-273, 1963.

4. Barsom, G., Lagoon Performance and the State of Lagoon Technology. EPA Technical Service Report R2-73-144, Washington, DC, 1973.

5. Champlin, R. L., Supplementary Aeration of Lagoons in Rigorous Climate Areas. EPA Water Pollution Control Research Series, October, 1971.

6. Christianson, C. D., Coarse Bubble Diffusers for Aerated Lagoons in Cold Climates. EPA Artic Environmental Research Laboratory, College, AK, Working Paper No. 17, January, 1973.

7. Upgrading Wastewater Stabilization Ponds to Meet New Discharge Standards. Proceedings of a Symposium held at Utah State University, Logan, UT, PRWG159-1, August 21-23, 1974.

8. Reynolds, J. H., R. E. Swiss, C. A. Macko, and E. J. Middlebrooks, Performance Evaluation of an Existing Seven Cell Lagoon System. EPA-600/2-77-086, August, 1977.

9. Bowen, S. P., Performance Evaluation of Existing Lagoons, Peterborough, New Hampshire. EPA-600/2-77-085, August, 1977.

10. McKinney, R. E., Performance Evaluation of an Existing Lagoon System at Eudora, Kansas. EPA-600/2-77-167, September, 1977.

11. Shindala, A., and J. W. Stewart, Chemical Coagulation of Effluents from Municipal Waste Stabilization Ponds. Water and Sewage Works, 118(4):100-103, 1971.

12. Shindala, A., Nutrients and Algal Removal from Oxidation Pond Effluents. Presented at the Sixth Mississippi Water Resources Conference, Mississippi State University, Water Resources Research Institute, State College, 1971.

13. Graham, J. J. and R. B. Hunsinger, Phosphorus Reduction from Continuous Overflow Lagoons by Addition of Coagulants to Influent Sewage. Catalog No. En43-11/65, Minister of Supply and Services, Canada, 1977.

14. Boyko, B. I. and J. W. G. Pupke, Aerated Lagoons in Ontario: Design and Performance Considerations. Proceedings from International Symposium on Waste Treatment Lagoons, Ross E. McKinney (editor). Sponsored by the Missouri Basin Engineering Health Council, Kansas City, MO and the U. S. Department of the Interior, Federal Water Quality Administration, Washington, DC, 1970.

15. Duddles, G. A. and S. E. Richardson, Application of Plastic Media Trickling Filters for Biological Nitrification Systems. EPA-R2-73-199, June, 1973.

16. Stone, R. W., D. S. Parker, and J. A. Cotteral, Upgrading Lagoon Effluent for Best Practicable Treatment. J. Water Pollution Control Federation, Vol. 47, No. 8, August, 1975.

17. Borchardt, J. A., S. J. Kang, and T. H. Chung, Nitrification of Secondary Municipal Waste Effluents by Rotating Bio-Discs. EPA-600/2-78-061, June, 1978.

18. Process Design Manual for Phosphorus Removal, U. S. Environmental Protection Agency, Technology Transfer, April, 1976.

19. Allied Chemical Corporation, Industrial Chemicals Division, Valley Forge Executive Mall, 676 Swedesford Road, Wayne, PA 19087.

20. Stankewich, M. J., Biological Nitrification with the High Purity Oxygenation Process. Presented at the 27th Annual Purdue Industrial Waste Conference, Lafayette, IN, May, 1972.

21. Process Design Manual for Nitrogen Control, U. S. Environmental Protection Agency, Technology Transfer, October, 1975.

22. Weber, C. I., The Preservation of Phytoplankton Grab Samples. Transactions of the American Microscope Society, Vol. 87, 1968.

23. Standard Methods for the Examination of Water and Wastewater, 14th ed., APHA, AWWA, WPCF, 1975.

24. Prescott, G. W., How to Know the Freshwater Algae, 2nd ed., William C. Brown Company, Dubuque, IA, 1970.

25. Mulbarger, M. C., The Three Sludge System for Nitrogen and Phosphorus Removal. Presented at the 44th Annual Conference of the Water Pollution Control Federation, San Francisco, CA, October, 1971.

26. Palmer, C. M., Algae and Water Pollution. EPA-600/9-77-036, December, 1977.